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EXTREME TEMPERATURE AEROSPACE BEARING LUBRICATION SYSTEMS

by

L. A. Peacock and W. L. Rhoads

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS3-7912
TASK ORDER NO. 5

RESEARCH LABORATORY
SKF INDUSTRIES, INC.
ENGINEERING AND RESEARCH CENTER
KING OF PRUSSIA, PA.

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FINAL REPORT OF TASK ORDER NO. 5

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ABSTRACT

Angular-contact ball bearings (25mm bore) made with vacuum melted M50 steel rings and balls and M1 steel cages have been endurance tested at 600°F, 43,000 rpm and 459 lbs. thrust load with DuPont "Krytox" 143 AC perfluoro alkyl polyether lubricant. Bearings made of WB49 steel rings and M1 steel balls and cages have been endurance tested at 700°F and the same load and speed with Mobil XRM-177F hydrocarbon lubricant. Smearing failures predominated in both of these test series. These results indicate that Mobil XRM-177F provides marginal lubrication at 700°F, but, if adequately lubricated, WB49 steel bearings probably do not have any drastic reduction in-spalling fatigue life at 700°F. The results also indicate that it is unlikely that long-term operation can be realized at 600°F with Krytox 143AC and M50 steel bearings under the test conditions used.

In a second phase of the project lubricant film thickness measurements were made in the rolling contacts of ball bearings, similar to those used in Phase I endurance tests, by AC conductivity and capacitance techniques. Four different types of lubricants (synthetic paraffinic hydrocarbon, improved ester, polyphenyl ether, perfluoro alkyl polyether) used in previous endurance testing under related projects at varying speed (up to 43,000 rpm) load (up to 250,000 psi maximum Hertz pressure) and temperature (up to 700°F) conditions were used. It was found that elastohydrodynamic lubricant films exist at these extreme conditions but film thicknesses differ (are generally lower) from those predicted by isothermal theory and that considerable differences exist in the thickness of films formed by the various types of lubricants beyond differences predictable from their differing physical properties.

The methods evolved for use in this second phase of the Task are described in a Supplemental Report issued under separate cover concurrently with this Final Report.

FINAL REPORT OF TASK ORDER NO. 5

EXTREME TEMPERATURE AEROSPACE BEARING LUBRICATION SYSTEMS

by L. A. Peacock and W. L. Rhoads

SKF Industries, Inc.

FOREWORD

This is the Final Summary Report submitted in fulfillment of Task Order No. 5 under NASA Contract No. NAS3-7912 entitled "A Study of Extreme Temperature Aerospace Bearing - Lubrication Systems". It encompasses research conducted from November 18, 1966 through December 18, 1967 and previously reported in Monthly Progress Reports Numbers 1 through 12.

A Supplemental Report SKF AL68T075 describing experimental methods used in Phase II of this Task is being issued under separate cover concurrently with this Final Report and constitutes an integral part thereof.

SUMMARY

In this Task two phases of work were completed. The first Phase extended the endurance testing of 7205 angular-contact ball bearings at elevated temperatures and high speeds begun under NASA Contract NASw-492 and continued in Tasks 2 and 3 of the present contract. This first Phase includes 700°F tests with the most promising fluid found in previous work, the synthetic paraffinic hydrocarbon Mobil XRM-177F. Tests were also conducted at 600°F with DuPont Krytox 143AC, a recently developed perfluoro alkyl polyether. The second Phase investigated the lubricant film forming characteristics in rolling contacts of the base stocks of four lubricants, which have been tested in this and previous programs at a variety of speed, temperature, and load conditions. The investigation was made possible by using two new film measuring systems developed under Task 3 and 5 of this contract. In this report the findings of the two phases are reported separately, with reference both between them and to other programs made when necessary.

In Phase I, two groups of 25mm-bore (7205-size) angular-contact ball bearings made of vacuum-melted high-temperature tool steels were life tested, 2 bearings at a time in SKF Industries test rigs simulating typical high-speed aerospace auxiliary drive spindles. The rigs were inert gas blanketed to provide an oxygen content of less than one percent in the atmosphere over the lubricant.

A group of 18 bearings having WB49 steel rings, M1 steel balls, and silver plated M1 steel cages was tested at 700°F, and 43,000 rpm with a 459 lb. thrust load. Mobil XRM-177F, a synthetic hydrocarbon having an anti-wear additive, which was found to give good results in 600°F testing was used.

Smearing failures (gross metal transfer on the balls and grooves due to lubrication related thermal instability) occurred in eight of a total of 9 tests at lives of 6.3 to 46.3 hours (16.5 to 121.3 mill. revs.). In one of these tests, the mating bearing suffered a ball spalling failure at a life of 44.3 hours (115.9 mill. revs.). One of these tests was run with a reduced load (200 lbs.), one test used bearings having twice the normal cage clearance, and one used bearings having an experimental proprietary tungsten disulfide surface coating. In the ninth test of two more bearings having the tungsten disulfide coating (making a total of 4 coated bearings tested), one bearing failed by spalling fatigue of the inner ring at a life of 156.5 hours (409.4 mill. revs.). These results indicate that Mobil XRM-177F lubricant provides very marginal lubrication for these small bearings at 700°F.

A group of ten M50 tool steel bearings with silver plated M1 steel cages was tested in a manner similar to that described above at 600°F using DuPont Krytox 143 AC, a perfluoro alkyl polyether. All of these tests resulted in smearing failures at or shortly after start-up. In exploratory tests and in film measuring tests with the Krytox 143 AC fluid conducted for Phase II, smearing failures predominated at lives ranging up to 8.0 hours. Three spalling failures also occurred at lives between 1.2 and 16.9 hours. These results suggest that this fluid has

poor boundary lubricating qualities under the test conditions. It appears unlikely that long-term operation without lubrication-related surface distress can be realized unless a suitable additive package to improve boundary lubrication is provided. The tabulation below summarizes all 7205 bearing endurance testing (begun in 1962 under contract NASA-492 and continued to the present).

SUMMARY OF HIGH-TEMPERATURE 7205 BEARING ENDURANCE RESULTS

(43,000 RPM WITH N₂ BLANKET)

BRG. STEEL	LUBRICANT	TEMP. °F	THRUST LOAD LBS.	STRESS KPSI INNER OUTER	NO. BRGS. TESTED	NO.* BRGS. FAILED	PREDOM- INANT FAILURE MODE	BRG. L ₁₀ LIFE, MILL. REVS.		
								CALCULATED AFBMA	COMPUTER**	MAX. LIKE- LIHOOD EST.
M1	Esso Turbo Oil 35	500	365	<u>220</u> 233	30	2	Smear- ing	480	-	248
M1	Esso Turbo Oil 35	500	459	<u>244</u> 250	30	10	Spall- ing***	240	207	59
M1	Mobil XRM 177F	600	459	<u>244</u> 250	10	0	None	240	207	500
WB49	Mobil XRM 177F	600	459	<u>271</u> 268	30	3	Smear- ing	240	192	328
WB49	Mobil XRM 177F	700	459	<u>271</u> 268	18	9	Smear- ing	240	192	22
M50	Mobil XRM 177F	600	459	<u>269</u> 252	30	6	Spall- ing***	240	175	245
M50	DuPont Krytox 143AC	600	459	<u>250</u> 239	10	5	Smear- ing	240	142	10

* WHEN EITHER ONE OR BOTH OF THE SET OF TWO BEARINGS FAIL, ONE MATING BEARING IS COUNTED AS A SUSPENDED TEST.

** LIFE PREDICTED BY COMPUTER CALCULATION OF DYNAMIC LOADS AT HIGH SPEEDS, BASED ON AFBMA RATINGS. DUE TO CONTINUED REFINEMENT OF COMPUTER PROGRAM, LIVES AND STRESSES GIVEN HERE MAY DIFFER SLIGHTLY FROM THOSE REPORTED PREVIOUSLY IN (2, 4, 5).

*** WITH LUBRICATION DISTRESS (GLAZING).

These data indicate that derating is not necessary for prediction of spalling fatigue life with aircraft quality tool-steel bearings at the elevated temperatures up to at least 600°F, when adequate lubrication is provided. In the absence of adequate lubrication, the failure mechanism appears to be increasing thermal instability which decreases the internal clearance resulting in a smearing failure.

In Phase II, measurements were made of the lubricant film thickness at the ball-race contacts of a 7205-size bearing, operating in full-scale tests with temperatures ranging from 400°F to 700°F. Four different types of lubricants and an SKF-developed AC Conductivity and Capacitance film measuring system were used. Speed was 20,000 or 43,000 rpm, and load varied between 200 and 459 lbs. The lubricants were Monsanto MCS-354 (a polyphenyl ether), Sinclair Turbo-S Oil 15 (an ester) which is the base stock for Turbo-S 1048, (improved), Mobil XRM-109F (a synthetic paraffinic hydrocarbon) which is the base stock for XRM-177F, and DuPont Krytox 143AC (a perfluoro alkyl polyether).

The data obtained show that the thickness of lubricant films formed in rolling contacts by XRM-109F and Turbo-S Oil 15 is generally 1/2 to 3/4 of the theoretically computed isothermal values. For MCS-354 the oil film thickness was less than 1/2 the isothermal theoretical, and for Krytox 143AC almost equal to isothermal theoretical. The theoretical values for given conditions for XRM-109F, MCS-354, and Krytox 143AC were approximately the same while those for Turbo-S Oil 15 are about 1/2 of the others. The expected decrease of film thickness with decreasing speed, increasing load and, generally, with increasing temperature was noted as was a run-in phenomenon.

The ability to form EHD films is not the sole determining factor in predicting a fluid's success as a bearing lubricant. Proper boundary lubricating and heat transfer properties are also essential. However, film thickness is a measure of how well a fluid prevents metal-to-metal asperity contact occurrences between bearing rolling elements and hence how well the fluid prevents surface initiated types of bearing failure. With this limitation in view, the results of film thickness measurements correlate reasonably with endurance test results of this program. Results also correlate reasonably well with data obtained with full-scale aircraft mainshaft size bearings under NASA Contract NAS3-6267. It is apparent from the results obtained to date that the EHD film measuring system is a tool for predicting the performance of lubricants in rolling element bearings.

PHASE I - ENDURANCE TESTINGINTRODUCTION

7205-size angular-contact ball bearings have been tested in the SKF Research Laboratory at high speeds and temperatures on a continuing basis beginning in 1962 with NASA Contract NASw-492 and continuing through Task Orders Nos. 2, 3 and 5 of NASA Contract NAS3-7912. The results of the earlier programs have shown that bearings made of M50, M1 and WB49 tool steels will run to lives at least as great as and in most instances 2 to 3 times greater than the AFBMA rated catalog life when tested at 600°F with adequate lubrication. The majority of these previous tests were run with Mobil XRM-177F, a synthetic paraffinic hydrocarbon oil containing an anti-wear additive.

It was the purpose of the endurance test portion of the present program to extend the earlier results with WB49 steel bearings and XRM-177F lubricant to 700°F and to include tests of M50 steel bearings at 600°F using DuPont Krytox 143AC, a perfluoro alkyl polyether lubricant which has shown promising performance in other programs (1)*. The information obtained in this testing along with the previous results will be examined using knowledge obtained in the lubricant film measuring phase of this program to gain insight into the effect of lubricant film thickness on high-speed, high-temperature bearing performance.

TEST RIGS

Three high-speed, high-temperature bearing test machines developed by SKF Industries, Inc. were used on this Task as in all previous projects of this series. Two machines used for endurance tests were fitted with constant speed 43,000 rpm drives. A special Monel test housing assembly (to limit corrosion damage) similar in construction to the standard stainless steel housing assembly was utilized for certain of the tests with DuPont Krytox 143AC lubricant and M50 steel bearings. In several of the exploratory tests with Krytox 143AC, the Monel test housing was fitted to a variable speed drive so that slow speed (20,000 rpm) start-up could be tried. Full speed (43,000 rpm) start-up contributed to smearing failures of the M50 bearings with lubricants having poor boundary lubrication properties.

*Numbers in parenthesis refer to References at the end of this report.

A layout sketch of a test rig housing assembly is shown in Enclosure 1 and its design and operation are described in detail in (2,3,). Essentially, each rig tests two 7205 angular-contact ball bearings mounted on the same shaft and thrust loaded against each other by a dead weight and lever system. Screw pumps machined in the shaft between the two test bearings circulate the test lubricant from a 2000 cc sump through the bearings and back to the sump through sight-flow tubes used as a visual check on the lubricant flow through the bearings. Nitrogen gas is supplied as an inert blanket over the oil in the sump and to both ends of the test bearing housing. Mass spectrometer analysis of the atmosphere in one rig during a typical test indicated an oxygen content of 0.96%. Lubricant is replenished periodically to the sump as it is lost by evaporation and by slight leakage through the labyrinth seal on the drive end of the shaft.

Each rig is driven through a speed-increaser gearbox and quill coupling to the housing assembly. The constant speed machines are fitted with 60-horsepower AC induction motors while the variable speed machine is fitted with a 50-horsepower DC motor with speed adjustment through a Microstat control (made by Westinghouse). Each rig is located with its drive in an explosion-proof test cell. Overall views of one test rig in its test cell and its control cabinet located outside the cell are shown in Enclosures 2 and 3, respectively. Test bearings and oil temperatures are maintained by electrical cartridge-heaters in the rig housing and sump walls. The heaters are controlled by time-proportioning on-off temperature controllers. Temperature fluctuations are evened out by the relatively massive steel sections in which the heaters are imbedded. At the high bearing thrust loads and speeds used for endurance testing, however, the test bearings themselves generate almost enough heat to maintain the rig temperature at 500°F to 600°F. Therefore, fan cooling of the housing is employed to the degree necessary to maintain some heater input power for temperature control purposes.

TEST BEARINGS

The rings and balls of the test bearings for the endurance testing phase of this program were manufactured from aircraft bearing quality CVM M50 and WB49 tool steels. These are two of three steels (CVM M50, CVM M1, and CVM WB49) selected at the beginning of this program. The available fatigue life, high-temperature stability and long-term hot hardness data reviewed in (2,3) show these steels to have the most promise as candidate high-temperature bearing materials (for operation up to 600°F, 800°F and 1000°F respectively). WB49 steel bearings (SKF 7205 VAR) have been successfully endurance tested at 600°F with the hydrocarbon lubricant XRM-177F containing an anti-wear additive in a previous Task (4). Since this bearing steel is potentially capable of operation up to 1000°F, it was decided to test a similar group of WB49 steel bearings (SKF 7205 VAK) at a temperature of 700°F with the same XRM-177F lubricant.

M50 steel bearings (SKF 7205 VAG) have been successfully endurance tested in previous work (5) at 600°F with the same XRM-177F lubricant. It was decided to test a second group of M50 steel bearings (SKF 7205 VAP) with DuPont Krytox 143AC perfluoro alkyl polyether oil which has shown promise in tests of mainshaft size (125mm bore) ball bearings (1).

The composition, hardness and estimated maximum operating temperature capability of the two selected bearing steels (and also data on M1 steel for comparison) are given in Enclosure 4. The design and specifications of the 7205 VAR test bearings having WB49 steel rings and M1 steel balls are given in Enclosure 5. The design and specifications of the 7205 VAP test bearings having M50 steel rings and balls, which were manufactured in a previous Task (4), are given in Enclosure 6.

The cages used in all test bearings were made of M1 steel heat treated to a hardness of Rc 57 to 60 and electroplated with silver to a thickness of 0.001" to 0.002". This cage material, and the designs shown in Enclosures 7 and 8 for the bearings having counter-bored outer and inner rings, respectively, are based on the results of previous studies (2,6) indicating good performance under extreme lubrication conditions.

The inner and outer rings of 7205 VAR bearings were made from the same heat of CVM WB49 steel and were heat treated together. The balls in the VAR bearings are from one heat of CVM M1 steel. The inner and outer rings of the 7205 VAP bearings were made from the same heat of CVM M50 steel and were heat treated together. The results of trace element analyses of this heat are given in Enclosure 9. The balls are from another heat of CVM M50 steel. The analysis of each lot of steel obtained for test bearings was checked and found within the limits given in Enclosure 4. Steel samples from each heat treatment lot were checked metallurgically for proper structure and hardness as listed in Enclosure 4. Dimensional measurements before testing on all bearings used in the endurance testing phase of this Task are given in Enclosure 10.

TEST LUBRICANTS

A sufficient quantity of Mobil XRM 177F lubricant was obtained under Task 2 of this program to complete tests with WB49 steel bearings. The oil used in this Task is from the same lot as that used in Task 2 (4) and Task 3 (5), and typical properties are given in Appendix I. Mobil XRM-177F lubricant contains a proprietary anti-wear additive in a base stock designated XRM-109F, a synthetic paraffinic hydrocarbon. Much data showing excellent performance has been acquired with this lubricant in 600°F tests of 205-size bearings made of M50 and M1 tool steels (2,4,5) and they indicated that operation at 700°F may be possible. Promising performances was also obtained in tests of jet-engine mainshaft-size (125mm bore) ball bearings at 700°F with this lubricant (1).

Forty gallons of DuPont Krytox 143AC lubricant were obtained for the M50 steel bearing tests of the current program. Krytox 143AC is a perfluoro alkyl polyether oil which was selected for this program based on promising performance in jet-engine mainshaft-size (125mm bore) ball bearings (1) and also for comparison with previous tests (5) of M50 steel bearings at 600°F with XRM-177F lubricant. Typical properties of this lubricant are given in Appendix I.

TEST PROCEDURE

The standard procedure used for conducting the bearing lubricant endurance tests reported here is as follows:

1. The rig is assembled with the test bearings and an initial charge of test lubricant in the sump. The load is applied, all valves in the oil lines are closed, except the inboard bearing drain valves which are set at one turn open (the specified setting for 43,000 rpm operation), and the nitrogen blanket gas flow is started over the oil in the sump.

2. The rig is preheated for about an hour with both the housing and sump heater controllers set at 300°F.

3. The rig is started by first increasing the nitrogen flow to the sump wide open and closing the sump vents to prime the screw pumps on the test shaft, and when oil starts to flow out the drive-end labyrinth seal with the shaft rotated slowly by hand, the sight-glass outboard drain valves and sump vent lines are opened simultaneously with starting the drive motor. In the normal high-speed start-up endurance tests, the test rig achieves a top speed of 43,000 rpm in approximately 3.5 seconds. (The tests of the WB49 steel bearings were conducted in this manner). In slow-speed start-up, the speed control for the variable speed DC motor is set so that the test rig comes first to a speed of approximately 20,000 rpm, which is then gradually increased to 43,000 rpm allowing adequate time for the test bearings to "equalize" their temperature with the housing thus avoiding thermal imbalances which could lead to failure by reduction of bearing internal clearance. 20,000 rpm is the minimum start-up speed required for the screw pump

to prime and several of the M50 steel bearing tests were conducted in this manner.

Then the nitrogen flow to the sump is reset to the preheat level, the nitrogen flow lines to the housing cavities are opened, the sump heaters are turned off and the housing heater controller is set to the test temperature.

4. The test bearing outer-ring temperatures are monitored every 6 minutes by the central data collection system described in (2) and as the test temperature is approached either one or two cooling fans are turned on. The position and number of fans is determined by "cut-and-try" during the first hour of running. The final fan placement is selected to provide a sump temperature cooler than the bearings and to leave some power input to the housing heaters for bearing temperature control.

5. Test lubricant lost by evaporation and seal leakage is replenished to the sump during each test at a rate of about 25cc per hour for 600°F tests. This figure was about 100cc per hour at 700°F due to higher leakage and evaporation rates. Automatic shut down of the rig occurs if the oil pressure from either screw pump decreases below a preset limit of 30% of the normal oil pressure or if a vibration-sensitive switch fastened to the load lever arm detects an abrupt increase in rig vibration level. The rig is disassembled for inspection of the test bearings if manual rotation of the shaft with the bearings under load indicates any unusual roughness in the bearings. Testing of both bearings is terminated when either test bearing fails. The other bearing is then treated as a suspended test.

TEST RESULTSA. WB49 Steel Bearings and Mobil XRM-177F at 700°F

A total of eighteen (WB49 steel) 7205 VAR bearings were run in nine tests (two bearings per test) with Mobil XRM-177F lubricant. The results of these tests are summarized in the following table in chronological order. Unless otherwise noted, test conditions were 700°F bearing outer-ring temperature, 43,000 rpm inner-ring speed, oil inlet temperature of 620° to 680°F, and a thrust load of 459 lbs. (corresponding to 271,000 psi and 268,000 psi Hertz stress on the inner and outer rings respectively).

Tabulation of Test Results

Bearing L10 life computed according to AFBMA methods (7) is 240 mill. revs. and 192 mill. revs. when dynamic loads at these high speeds are considered for 459 lbs. thrust load.

<u>Test No.</u>	<u>Special Conditions</u>	<u>Test Life (Hrs.)</u>	<u>Test Results</u>	
			<u>Type Failure</u>	<u>Mating Brg. Condition</u>
1	None	44.4	Smeared	Spalled Balls
2	None	41.7	Smeared	Debris Dented
3	None	19.2	Smeared	Surface Distress
4	None	6.3	Smeared	Debris Dented
5	None	31.5	Smeared	Debris Dented
6	200lbs. load	7.0	Smeared	Debris Dented
7	Both brgs. coated with	156.5	Spalled	Debris Dented
8	experimental tungsten disulfide proprietary coating*	10.8	Smeared	Debris Dented
9	Cage to land clearance increased from normal 0.008" to 0.016".	46.3	Smeared	Debris Dented

* "Dicronite" supplied by Miniature Precision Bearings, Inc. of Keene, New Hampshire.

A more detailed summary is included as Enclosure 11. Enclosure 12 shows an unfailed WB49 bearing from 600°F testing while Enclosure 13 shows a typical smearing failure from this series. Enclosure 14 shows the bearing with spalled balls (Test 1) and Enclosure 15 shows the spalled inner ring from test 7.

As can be seen from the summary, eight of nine tests resulted in smearing failures in spite of surface coatings, decreased load, or increased cage clearance. In one of the eight tests, a mating bearing was found to have several spalled balls. In a ninth test of two coated bearings, an inner ring spalling failure occurred. Based on these data a maximum likelihood estimate computed according to the method in Appendix III of (2), gives $L_{10} = 63.1$ hours (162.5 mill. revs.) for the spalling failures and $L_{10} = 8.1$ hours (21.5 mill. revs.) for both smearing and spalling failures. These estimates do not include the test run at 200 lbs. thrust load.

B. M50 Steel Bearings and DuPont Krytox 143AC at 600°F

A total of twelve new 7205 VAP and several run-in 7205 VAG bearings, both manufactured from M50 steel, were run-in thirteen tests (2 bearings per test) using DuPont Krytox 143AC perfluoro alkyl polyether lubricant. Nominal test conditions were 600°F bearing outer-ring temperature, 43,000 rpm inner-ring speed, and a thrust load of 459 lbs. corresponding to a maximum Hertz stress of 250,000 psi on the inner ring. Unless otherwise noted, bearings were uncoated and tests were run in a Monel housing with high-speed start-up procedures described on page 12. The results of these tests are summarized in chronological order in the following table. A more complete summary is included as Enclosure 16.

TABULATION OF TEST RESULTS

BEARING L₁₀ LIFE COMPUTED ACCORDING TO AFBMA METHODS IS
 240 MILL. REVS. AND 142 MILL. REVS. WHEN DYNAMIC
LOADS AT THESE HIGH SPEEDS ARE CONSIDERED FOR 459 LBS. THRUST LOAD

<u>Test No.</u>	<u>Special Conditions</u>	<u>Type Failure</u>	<u>Life (Hrs.)</u>
1	None	Smearing	Start-up Fail.
2	None	Smearing	Start-up Fail.
3	As 1, except coated brgs. 1), 2)*	Smearing	Start-up Fail.
4	Coated brg.1); slow start.2)	Smearing	0.4 after start-up
5	As 4	Smearing	1.1 after start-up
6	Lowered housing; othwise as test no. 4. 3)	Spalling	1.2 after start-up
7	As 6	Smearing	0.3 after start-up
8	As 6 except in stainless steel housing instead of Monel	None	0.5 (manual shut down)
9	As 8, except high speed start	Smearing	Start-up Fail.
10	As 8	Spalling	6.4 after start-up
11	As 8	Smearing	Start-up Fail.
12	As 8	Smearing	0.1 @ 43,000 rpm
13	As 8	Smearing	8.0 @ 43,000 rpm

See page 15 for footnotes

NOTE: All mating bearings showed at least some signs of surface distress.

- 1) Coated with Dulite, a black oxide coating which has been shown to improve boundary lubrication.
- 2) Slow speed start-up as explained on page 10.
- 3) Test housing lowered relative to drive quill for reasons set forth below.

As can be seen, smearing failures at very short lives predominated. The black oxide coating, known to be of benefit in instances where there is marginal lubrication, did not seem effective in those tests. Indeed, the coating was worn through in the ball track in mating bearings examined even after short running times. This may be due to attack of the coating by the lubricant which is known to be corrosive.

One fact which was noted, and can be seen in Enclosure 17, is that all smearing failures occurred on the drive end bearing (the one closest to the gearbox). As can be seen from Enclosure 17, where there were early failures, (less than 1 hour running) a majority of them occur on the drive end throughout the program. Failures after an hours operation are about evenly divided between the two locations. Upon careful investigation it was found that, due to thermal expansion of the housing support arms, seen in Enclosure 2, the test shaft center line was about 0.010" above the centerline of the gearbox output shaft at a bearing housing temperature of 600°F. Due to the rigid mounting of the quill drive, this misalignment could cause up to 50 lb calculated radial load on the drive end bearing. In all tests after #5, this was compensated for by setting up the housing lower than needed for alignment room temperature. In spite of this, smearing failures still predominated, if perhaps after somewhat longer running times. There also were two spalling failures.

In addition to the thermal misalignment, it was found when examining fits, tolerances, etc., that, due to the sliding fit of the load plug (in which the load-end bearing is mounted as shown in Enclosure 1) in the housing assembly, plus the relatively thin and somewhat flexible load plug bearing mounting system, the load end of the test rig is slightly more accommodating to bearing outer-ring thermal expansion than is the drive-end mounting. The additional clearance afforded the load-end bearing is helpful in preventing or at least postponing early smearing type failures as a result of loss of bearing clearance. The drive-end bearing, mounted directly in the housing block, does not enjoy the same extra "compliance" and failures precipitated by loss of internal clearance will generally occur first on this bearing. In some of the tests, bearings were run in a stainless steel test housing since it was thought that there could be some parameter being overlooked in the previously untried Monel housing which might be contributing to early failures. As can be seen from the data, this did not change the failure mode.

In short then, it seems that there is some slight bias inherent in the rig design that causes a majority of short life smearing failures to take place on the drive end. It appears that this only takes place in the presence of very marginal lubrication conditions.

Irrespective of this bias, the tests with Krytox 143AC fluid showed that successful operation could not be obtained under the test conditions.

In the film measuring part of this task, to be described as Phase II, similar 7205 VAP bearings were run with the same lot of this lubricant. In this work one new uncoated bearing ran for 1.65 hours at 300 lbs. load and was in very good condition after testing as shown in Enclosure 34. A second new uncoated bearing ran a total of 25.4 hours (2.4 hours at 300 lbs. load, 36.1 hours at 459 lbs. load) and had moderate surface distress after testing as shown in Enclosure 35. A third new coated bearing ran a total of 16.9 hours at 459 lbs. load and had suffered a spalling failure as shown in Enclosure 38. All bearings were run at 43,000 rpm with temperatures

ranging from 400 to 700°F. Slow speed start-up procedures were used in all tests. These runs were, accordingly, more successful than the "endurance runs" and this is attributed, except for the last test, to the lesser test load. The more gradual temperature increase may also have been helpful to run-in.

DISCUSSION - PHASE I

A. Testing at 700°F with Mobil XRM-177F & WB49 Steel Bearings

During these tests the predominant failure mode was smearing at short lives. Only one set ran to approximately 1.7 times the AFBMA computed life (see (2), Appendix I) before failure by spalling. In a previous program (4) it was found that this bearing-lubricant combination ran to more than twice the AFBMA computed life at 600°F although the predominant failure mode was again smearing. Since these smearing failures are lubrication related and are not related to fatigue spalling, it can be concluded from these two programs that very little if any reduction in fatigue life of this steel occurs, at least up to 600°F, provided the bearings are adequately lubricated. The type of failures encountered in this program are very similar to those described in (1) with aircraft mainshaft size bearings using this lubricant-steel combination in the 700°-800°F region. As can be seen from Appendix I of (2), one of the parameters governing elastohydrodynamic (EHD) lubricant film thickness is bearing size. Thus, a test in the 600°-700°F region with 7205 size bearings operates at a calculated film thickness/roughness ratio, h/σ (see Appendix II) roughly comparable to the h/σ value calculated for a test in the 700°-800°F region run with mainshaft size bearings.

The most likely mechanism of these smearing failures is the self-aggravating loss of bearing internal clearance due to thermal instabilities and related localized breakdown of lubrication in these high temperature bearings. As has been discussed in (1,2) there are three interrelated mechanisms by which these thermal instabilities may come about:

- 1) By a lubricant film too thin to prevent considerable asperity contact between bearing elements.
- 2) Given asperity contacts, by lack of adequate boundary lubrication in the form of bearing surface coatings or lubricant additives.
- 3) By a change or breakdown of heat transfer properties of the fluid, possibly related to surface wetting ability.

It was found in the film measuring portion of this task (to be described as Phase II in this report) that with XRM-177F lubricant, operation with 7205 bearings is in the partial EHD region in the 600-700°F range. The viscosity of XRM-177F is 30% lower at 700°F than at 600°F. Two ways present themselves to achieve reliable long-term operation in this temperature range. Firstly, by utilizing more viscous fluid such as Mobil XRM-187F (same basestock as XRM-177F but about 20% more viscous at 700°F). And secondly, by improving boundary lubrication through surface coatings such as the proprietary tungsten disulfide coating which was used on several bearings in this test and was successful in preventing smearing. At the present time, there is no known way to improve the heat transfer characteristics of given lubricants if indeed this is a problem but there is a distinct possibility that these properties differ from one fluid basestock to another.

B. Testing at 600°F with DuPont Krytox 143AC & M50 Steel Bearings

Testing with this fluid resulted in a preponderance of smearing failures at very short lives. This correlates with results of previous work (5) in which M50 steel bearings lubricated with XRM-177F oil were found susceptible to surface distress at 600°F, most probably due to M50's reduced hardness at this temperature. However, the performance with Krytox 143AC was much inferior to that with XRM-177F. Krytox 143AC was also used in the mainshaft size bearing tests described in (1). With WB49 steel bearings, it performed well to about 700°F; however,

in the 750°F region, sudden smearing failures often occurred. Considering the difference in steel (higher hardness) and the previously described size effect on EHD film condition, the results obtained in the present 7205 size bearing tests appear in agreement with those for the mainshaft size bearings.

It was found in the film measuring part of this Task (Phase II) that with Krytox 143AC, at the start of a test the EHD film thickness was such that there should not have been a significant number of asperity contacts at 600°F. After a few hours running, however, the film thickness/roughness ratio decreased to the point where there were considerable asperity contacts due to deterioration of the surface. Quite possibly the same surface deterioration took place more rapidly in the endurance tests.

Based on tests in the present Task, Krytox 143AC lubricant showed poor boundary lubricating properties. More reliable operation can probably best be realized by the addition of an effective additive package. No additives for Krytox 143AC were available at the time of the work herein reported.

PHASE II - FILM THICKNESS MEASUREMENTSINTRODUCTION

Since the emergence of elastohydrodynamic (EHD) lubrication theory describing the existence of lubricant films of finite thickness in loaded bearing contacts, numerous experiments have been performed to verify the theory and further examine the elastohydrodynamic phenomenon (8-12). Up to this time, most experiments were limited to element tests using such devices as two and four ball testers, roller to flat and roller to roller contacts, and others.* Film measuring techniques have included both an electrical DC conductivity method which has for some years been established as a means of instantaneously monitoring the occurrences of asperity contact between surfaces under partial EHD lubrication (14-16) and a capacitance technique. The capacitance method has been tested in the SKF Laboratory in a rolling four-ball tester for surfaces under full EHD lubrication (17).

Recently, SKF Industries, Inc., under Tasks 3 & 5 of this contract has succeeded in applying these techniques to full-scale bearings by developing a "film measuring system" which combines the use of a modified electrical conductivity method (using an AC signal) with the capacitance method (18). In this way both partial and full EHD lubrication regimes can be monitored. The film measuring system utilized in this work as well as the relation of electrical measurements to EHD film in 7205 size thrust loaded bearings is described in detail in the Supplemental Report to this Task published concurrently herewith which is bound separately.

In the film measuring phase of the present program, four different types of lubricants were evaluated using the SKF developed film measuring system to determine EHD film forming characteristics as a function of temperature and, in several cases, load and speed. The information obtained in these tests was then utilized in interpreting the behavior of similar fluids in endurance and screening tests which were conducted in this and other programs.

*Experiments with full scale bearings have been reported by Garnell & Higginson (13) and some exploratory tests were conducted in the SKF Industries Research Laboratory

The EHD lubricant film thickness measurements contained in this report represent the first successful work to reduce to practice in full-scale bearings the electrical film measuring techniques which heretofore were adapted only in element configurations. The instrumentation and method developed herein is considered a tool for the exploration of EHD film conditions and should find extensive use in future bearing and lubricant evaluation work.

BACKGROUND

It was stated in the Final Report issued under NASw-492 (2) that a correlation between elastohydrodynamic film condition and bearing-lubricant performance has emerged in past tests with 7205-size angular-contact ball bearings operated at temperatures above 500°F at speeds in excess of 20,000 rpm, using a variety of fluid lubricants. Specifically, the elimination of glazing type surface distress of the rings appears to require a film condition where the film thickness/surface roughness ratio, h/σ is greater than 1.5. It was also stated in the same Final Report that smearing (galling) type metal transfer occurrences between balls and grooves have caused numerous early bearing failures with some of the lubricants. These are attributed to the unsatisfactory boundary lubricating ability of the lubricants for the prevailing operating conditions which are believed to involve high instantaneous sliding velocities in the ball/groove contact, either because of accelerations when coming up to speed, due to uncertain ball-spin control in the presence of gyroscopic moments on the balls or due to thermal imbalance occurrences. The evidence used to support the mechanisms of failure postulated in (19) comes from film condition measurements performed in rolling-element configurations (20, 21).

It is recognized that extrapolation of film condition calculations to operating conditions of 500°F and higher, with the speed, geometry, and lubricant variables substantially different from those used as the basis of the calculations is an expedient. It is used in the absence of more direct data and is, at best, inaccurate, and at worst, misleading. In order, therefore, to better define the elastohydrodynamic lubrication conditions in high-speed high-temperature bearing tests direct experimental determination of the lubricant film variables is desirable. It should also be possible to determine what effect the many chemically different lubricants have on bearing performance.

of a suitable film measuring system for use with operating 7205-size bearings (and any other thrust loaded ball bearing) was undertaken in Task 3 of this contract (5). A film measuring system has been made operational for which theory and engineering development is reported in detail in the Supplemental Report AL68T075 issued concurrently with this Final Report.

Data obtained with the present system serve to establish film thickness as a function of operating parameters and the film thickness/roughness ratio as a function of bearing condition. The data also provides some information on the transient occurrences in the lubricant film that take place during acceleration and at incipient failure.

INSTRUMENTATION AND TEST RIG

The instrumentation system and modified variable speed test rig used in this program are described in detail in the Supplemental Report to this Task (18).

Test Bearings

Lubricant film measurements were conducted using a total of twelve M50 steel 7205 VAP bearings described in Phase I of this report with design details shown in Enclosure 6. The nine bearings used in the measurements were not black oxide coated since the presence of an insulating boundary lubricant coating interferes with the film thickness measuring system as explained in (18).

The cages used in all test bearings were similar in design to the standard M1 steel cages shown in Enclosure 8 but were made of a special non-metallic, high temperature polyimide material manufactured by DuPont de Nemours & Co., Inc., Wilmington, Delaware and designated as Vespel SP-1. The polyimide cage is used to prevent electrical ball-to-ball shorting of the measuring signal which would invalidate the probability analyses described in (18) which are used to convert measurement data to film parameters.

Three supporting bearings (non-test bearings) were used and these were of the standard 7205 VAP design as described in Phase I of this report and shown in Enclosure 6, having black

coated M50 steel rings and balls and silver plated M1 steel cages.

Test Lubricants

Five gallon quantities of four different lubricants were obtained for use in the film measuring phase of the program. These were Monsanto MCS-354 (a polyphenyl ether), Sinclair Turbo-S Oil 15 (an ester which is the base stock of Turbo-S 1048 Improved), Mobil XRM-109F (a synthetic paraffinic hydrocarbon and base stock of XRM-177F), and DuPont Krytox 143AC (a perfluoro alkyl polyether). Typical properties of these lubricants are presented in Appendix I. To avoid any misleading results caused by additive action at the contacting surfaces, as discussed in (18), base stock (additive-free) oils were used. In the case of the usual boundary lubrication additives used in small concentration it is generally thought that lubricants will exhibit EHD film forming characteristics similar to those of the base stocks from which they are derived because the additives do not change bulk physical properties of the fluids. The lubricant film thickness results presented in this report should, therefore, be applicable to the compounded oils (base plus additives) which have accumulated a considerable amount of testing experience in this as well as other programs (1, 2, 4, 5). A discussion of these lubricants follows.

a) Monsanto Chemical Company MCS-354-Polyphenyl Ether

This fluid is a mixed isomeric five-ring polyphenyl ether. It has excellent thermal stability, good oxidation resistance, good lubricity and radiation resistance. The fluid is produced by the addition of an oxidation inhibitor to Monsanto OS-124 lubricant. This type of additive (0.2% by weight organotin; carbon, hydrogen, tin) is not thought to effect the accuracy of the film measuring system because it is not believed to form an insulating surface layer. MCS-354 lubricant, then, has physical and lubrication properties similar to OS-124 lubricant. Endurance tests with OS-124 lubricant and 7205 size tool steel bearings in an earlier program (2) resulted in lubrication failures at 600°F or lower, at lives less than the calculated L₁₀ life.

b) Sinclair-Refining Company Turbo-S Oil 15-Ester Base Lubricant

Turbo-S Oil 15 is the base stock of Turbo-S 1048 (Improved) oil, the latter containing a proprietary boundary lubricating additive package. Turbo-S 1048 (Improved) oil has shown excellent high temperature capability in 700°F operation of jet engine mainshaft size bearings under simulated jet engine operating conditions (1).

c) Mobil Oil Company XRM-109F-Synthetic Paraffinic Hydrocarbon

This fluid is a hydrocarbon material synthesized by the polymerization of a fairly pure mono-olefin so that it can be considered a single chemical species composed of molecules of a chain length distribution depending on the type, method and degree of polymerization. It has reasonably good resistance to thermal degradation and is susceptible to additive improvement.

Mobil XRM-109F lubricant from two lots (lot 2 and lot 3) was used to perform film measurements reported herein. A very slight viscosity difference, considered insignificant for film measurement results, exists between the two lots as seen in Appendix I.

In an earlier research program (2), endurance tests with XRM-109F lubricant and 7205 size tool steel bearings resulted in a superficial pitting or "glazing" type of surface distress in the bearing raceways and also bearing smearing failures at relatively low lives. This fluid, without additives is therefore considered unacceptable for long term bearing operation at temperature in the 600°F range. However, in the same program and also in two other research programs (4,5) XRM-177F lubricant (XRM-109F containing a proprietary anti-wear additive), exhibited very good performance for long term bearing operation at 600°F (no derating in bearing catalogue life required) and for shorter times at up to 750°F. XRM-177F lubricant was also used in endurance tests at 700°F conducted in this present task with results discussed in Phase I of this report.

d) DuPont Company Krytox 143AC-Perfluoro Alkyl Polyether

This fluid is a perfluorinated polyether having excellent thermal and oxidative stability and high temperature viscosity (2.1cs at 500°F). It does, however, exhibit some corrosive effects on martensitic steels at temperatures above 550°F which somewhat limits its usefulness by dictating the use of special nickel alloys for all wetted parts, other than bearings, for extended test runs. This fluid has appeared favorable in preliminary bench-type screening tests both at NASA and SKF Industries, Inc., (2) and has also shown promising performance in simulated jet-engine mainshaft bearing tests at temperatures up to 700°F (1). The fluid was also used in attempted endurance tests of 7205 bearings made of M50 steel at 600°F in the present program with results discussed in Phase I of this report.

TEST PROCEDURES

The procedure used for all film measurements reported here is as follows unless otherwise indicated:

1. Prior to running a test series, the surface roughness values of the test bearing rolling elements (rings and balls) are measured and the composite rms surface roughness value of the bearing, σ , is computed as shown in Appendix II. Groove profile traces of some bearings may also be made prior to testing as needed.

2. The rig is assembled and checked to insure that all electrical connections to the measuring system are properly made. The instruments comprising the measuring system are allowed to warm-up for approximately one half hour before making the necessary pre-test settings as specified in (18). The rig is started in accordance with step No's. 1, 2 and 3 of the test procedure described in Phase I of this report (page 10) and is run in accordance with step No. 5 given there. Slow speed start-up procedures are always used.

3. After reaching the prescribed test speed, lubricant film measurements are taken at each of the specified temperatures as measured at the bearing outer ring by means of a thermocouple and a precision potentiometer, unless the film is too thin to be measured in which case the test is terminated. Measurements are also taken at several intermediate temperatures. After completing all measurements, the rig is manually shut down and allowed to cool. After cooling, a sample of the test oil may be taken for chemical analysis. If desired, the rig can later be re-started and additional tests with the particular bearing-lubricant combination may be run.

4. The rig is disassembled and the test bearing and supporting bearing are visually examined. The post-test surface roughnesses of the test bearing rolling elements (rings and balls) are measured. Profile traces of the test bearing rings may also be made if required. In instances where the test bearing shows severe surface distress, it is sometimes impossible to make meaningful roughness measurements or traces; however, a photographic record of the tested bearing is always kept. Supporting bearings which are not failed or damaged, are replaced in the rig and used in following tests.

5. The raw measurement data obtained from the tests are reduced to film parameters (h/ϕ ratios or film thickness) which are plotted against temperature with curves following data points very closely. The curves thus plotted are presented in Enclosures 19 (A&B) through 26 (A&B) with "A" lettered enclosures being composites of the individual test runs with a given oil and "B" lettered enclosures showing the individual test runs including data points. For conductivity, data obtained using the 5 kilohms resistance were plotted. Of the three resistances used for acquisition of conductivity data (5, 15 & 50 K Ω) 5 kilohms was chosen as most closely satisfying the guidelines set forth in (18). Data reduction is accomplished through the use of "calibration" curves developed and presented in (18). For comparison purposes, the isothermal theoretical h/ϕ vs. temperature curve is arrived at using the computational method presented in Appendix I of (2). Values for pressure-viscosity coefficient were obtained by means of Appeldoorn's empirical relations (22), and also using manufacturer supplied lubricant viscosity data for the various bearing temperatures listed on page 27.

TEST RESULTSGeneral

Film measurements were taken at the following nominal temperatures for each test condition with each lubricant: 400°, 450°, 500°, 550°, 575°, 600°, 625°, 650°, 675°, and 700°F. In many instances values were also obtained at intermediate temperatures. In some cases, to be discussed, the film thickness was too low to record data. Further in the tests with DuPont (Krytox 143AC) lubricant, film thickness data could not be obtained at temperatures much below 500°F due to the rapid temperature rise of the test bearing when this lubricant was used. On the other hand, in tests with Sinclair Turbo S Oil 15, it was possible to obtain data at temperatures as low as 300°F in some tests.

Since there were a number of repeat runs at the various conditions, it was later possible, by averaging the data, to plot a rough curve of temperature increase vs time for each oil tested at similar conditions in the same rig. These data offer comparisons between the heat generation rate with the various oils tested and are given in Enclosure 18.

The lubricants were tested at the following conditions:

<u>Fluid</u>	<u>Thrust Load (Lbs.)</u>	<u>Speed (rpm)</u>	<u>Max. Hertzian Stress (Psi X 1000)*</u>	
			<u>Inner</u>	<u>Outer</u>
Mobil	459	43,000	250	239
XRM-109F	300	43,000	215	218
	200	43,000	186	203
	345	20,000	239**	209**
Monsanto				
MCS-354	300	43,000	215	218
DuPont				
Krytox	300	43,000	215	218
143AC				
Sinclair				
Turbo S	300	43,000	215	218
Oil 15				

*Calculated for the dynamic conditions using a computer solution.

**Interpolated values (between computer calculated stress values for thrust loads of 300 and 360 lbs.

The results of these studies are presented as h/σ vs temperature plots in Enclosures 19 through 26. The computed isothermal theoretical film thickness based on formulas given in (2) were used to calculate theoretical h/σ curves also given for comparison in these enclosures. Detailed descriptions of the test series run with each oil follow. Discussion of the results and conclusions are presented in the section thereafter.

FILM MEASUREMENTS

a. Mobil XRM-109F

Four series of film measuring tests were conducted with this lubricant. Three test series were run at 43,000 rpm at bearing thrust loads of 459,300 and 200 lbs. respectively and one test series was run at 20,000 rpm at a thrust load of 345 lbs. Maximum inner and outer ring Hertzian contact stresses computed for the thrust loads used and taking the dynamic forces of the bearings at speed into account are given in the preceeding paragraphs.

Of the test series, No.'s 1, 2 and 3 were run at 43,000 rpm at thrust loads of 459,300 and 200 lbs. respectively. Results of lubricant film measurements for these three test series are given in Enclosures 19, 20 and 21 respectively. A total of 5 film measuring tests (1B, 1C, 1D, 1E, 1F) comprise series No. 1; 5 tests (2A, 2B, 2C, 2D, 2F) comprise series No. 2; and 3 tests (3A, 3E, 3F) comprise series No. 3. Two test bearings (brgs. #1 and #2) were used for the three test series. Both bearings already had a few hours of running time on them before being used in the film measuring tests. Bearing #1 was used for all tests except 2F, 3E and 3F for which tests bearing #2 was used. Bearings #1 and #2 had composite roughness values when new, of $\sigma = 2.6$ and 2.5 microinches rms, respectively and the above listed Enclosures show that no significant difference existed in the film ratio results for the two bearings.

In comparing the tests, three main findings become apparent.

First, in the lower portion of the temperature range, below 600°F, experimentally measured film thicknesses are on the order of 1/2 the theoretically predicted (isothermal) film thicknesses.

Second, as predicted by isothermal theory, the measured film thickness decreases with increasing load.

Finally, in each of the test series, an unexpected minimum in the film thickness curves is seen to occur between 500° and 600°F, i.e. film thickness drops with temperature up to these values but appears to increase above them. In tests 2F and 3F, film thickness dropped below the detectable level of the film measuring system as is indicated in the referenced Enclosures, but then increased again around 600°F. This rather unexpected phenomenon is discussed in the following section of this report.

Both test bearings accumulated more than 30 hours of operation at 43,000 rpm during completion of test series No.'s 1, 2 and 3. The final appearance of the two bearings is shown in Enclosures 27 and 28, along with data on total hours at various loads and also surface roughness. The inner and outer races of both bearings show glazing and pulling type surface distress. Post-test roughness measurements of the bearing running surfaces given in Enclosures 27 and 28 for bearings #1 and #2 respectively show an increased roughness for the inner rings (75% and 50% increase respectively), most likely due to the surface distress of both bearings. The outer rings showed a drop in roughness (10% and 20% respectively).* The balls of both bearings also show increases in roughness.

*It is recalled that the lubricant used is additive free

Mobil XRM-109F lubricant from two lots was used in the three test series discussed above. Lot 2 oil was used for tests 2F, 3A and 3F; all other tests in these three series were with lot 3 oil. No difference in results appears between the two lots.

Test series No. 4 was run at 20,000 rpm and 348 lbs. thrust load. This thrust load was selected to give a maximum outer ring Hertzian contact stress comparable to the maximum inner ring Hertzian contact stress with a 459 lbs. thrust load. Three tests (4A, 4B, 4C) comprise this test series. Film measurement results are given in Enclosure 22. A new bearing (#3) was used for this series and had a composite roughness value of $\sigma = 2.5$ microinches rms. Starting with test 4A, each successive test resulted in slightly higher measured film thicknesses suggesting some bearing run-in phenomenon. Capacitance results of test 4C show near theoretical film thicknesses at temperatures somewhat less than 400°F (theoretical isothermal film thickness at these conditions is about 2/3 that at 43,000 rpm and 459 lbs. load). Film thickness falls off quickly as temperature increases in the 400°F range as evidenced by the high slope of the curves. Tests were discontinued when film thickness dropped below the measurable range between 500° and 550°F in test 4B and 4C and at approximately 450°F for test 4A. There are no capacitance measurements for test 4A since film thickness in this test was below the range of the capacitance measuring method. The test bearing was removed after the test series and is shown in Enclosure 29 along with data on total hours and surface finish. Enclosure 36 shows the glazed condition of the support bearing used in all tests with this fluid.

It is seen that the surface roughnesses of both rings decreased by some 10% to 20% while the roughness of the balls increased slightly. The inner ring of the bearing shows some glazing and pulling type surface distress after 7.6 hours of operation. Mobil XRM-109F lubricant from lot No. 2 was used exclusively for this test series. The surface distress

that arose correlates with the relatively low film thickness found. As can be seen from Enclosures 19-22 there is generally better agreement between the experimental and theoretical film thickness results at 20,000 rpm than at 43,000 rpm. This is very likely due to the increased spinning heat generation at the higher speed, which increases the thermal effects unaccounted for in the theoretical calculation.

b. Sinclair Turbo-S Oil 15

Test Series No. 5 was conducted using Sinclair Turbo-S Oil 15 and consists of 7 film measuring tests (5A, 5B, 5C, 5D, 5E, 5F, 5G), the results of which are given in Enclosure 23. Two new test bearings were used for this series. The first bearing (brg. #4) was used in tests 5A, 5B, 5C and 5D and had a composite roughness value, when new, $R_a = 2.6$ microinches rms. The second bearing (brg. #5) was used for tests 5E, 5F and 5G and had $R_a = 2.5$ microinches rms. Capacitance data could be obtained only in one test, 5G. In test 5E, the film thickness was below the measurable level for the entire test with both conductivity and capacitance methods as indicated in Enclosure 23. Film thickness data are presented in this test series at temperatures beginning at approximately 250°F. This is the lowest starting temperature for any of the oils tested and is made possible by the low viscosity of the lubricant (one centistoke at 500°F) and consequent low viscous heat generation.

In observing the film ratio curves for this test series, several things can be seen.

First, experimental film thickness generally fall between $1/2$ and $3/4$ of theoretically predicted values (i.e. it is closer than with XRM-109F).

Second, the expected decrease in film thickness with increasing temperature takes place, however, as was the case with Mobil XRM-109F lubricant, an unexpected reversal of the film thickness/ temperature function was experienced in three of the tests (5A, 5F, 5G) at temperatures above 500°F. This again is discussed in a subsequent section.

Third, as was the case in test series No. 4 with Mobil XRM-109F lubricant, continued testing after mounting of a new bearing generally results in a progressively higher film thickness/roughness ratio. Thus, the tests 5A and 5E run with new bearings resulted in the h/σ values less than 2 while further testing with the same bearings resulted in h/σ values as high as 3 to 4 at the same operating conditions. This behavior suggests of run-in effects. The post-test appearance of bearing #4 and #5 is shown in Enclosures 30 and 31, respectively. Rather severe surface distress in both bearings is evident at lives of less than 8 hours which could be expected with the relatively low h/σ values, particularly in the presence of an additive free lubricant.

c. Monsanto MCS-354

Test series No. 6 was conducted with Monsanto MCS-354 lubricant and consists of 5 film measuring tests (6A, 6B, 6C, 6D, 6E). Lubricant film thickness results for this test series are presented in Enclosure 24. Two new test bearings were used. Bearing #6 having a composite roughness when new, of $\sigma = 2.5$ microinches rms was used in tests 6A and 6B and bearing #7 having $\sigma = 2.4$ microinches rms was used in tests 6C, 6D and 6E. Capacitance data could not be obtained in any of the 5 tests. In 6A and 6B the film thickness was below the measurable level even for the conductivity method or the duration of both tests. The operating procedure calls for the termination of a test if no EHD film thickness can be measured in order to avoid bearing failure. For this reason none of the tests in series 6 were run out to 700°F. Tests 6C, 6D and 6E showed measurable film thicknesses initially but it later dropped below measurable level between 500° and 550°F. The tests were then terminated. A run-in phenomenon was observed with the second bearing used in this test series (Brg. #7). In test 6C, using that new bearing, h/σ values of the order of 2 were obtained while in the succeeding tests 6D and 6E with the same bearing h/σ values between 2 and 4 were obtained. The appearance of the two tested bearings along with data on total running hours and surface finish are given in Enclosure 32 and 33. Bearing #6, which was used in tests 6A and 6B, where no measurable films were obtained, showed severe surface distress as seen in Enclosure 32 after only

1.75 hours total operation. Bearing #7 on the other hand, used in tests 6C, 6D and 6E where measurable films were obtained, was not surface distressed as seen in Enclosure 33 after 2.85 hours total operation. Post-test surface roughness measurements of bearing #7 given in Enclosure 33 showed a slight decrease in roughness for the inner ring while the balls showed an increase.

d. DuPont Krytox 143AC

Test series No. 7 was run with DuPont Krytox 143AC lubricant and consists of three tests (7A, 7B, 7C) at 300 lbs. load. Two additional tests (7D, 7E) not originally planned were also run at a thrust load of 459 lbs. for possible correlation with Phase I endurance results which show a history of bearing smearing failures at low lives. One of these two latter tests (7E) was run for an extended period (17 hours).

Two new test bearings (#8 and #9) having composite roughness values of $R_a = 2.4$ and 2.3 microinches rms respectively were used in this series. Bearing #8 was used in tests 7A and 7B, bearing #9 was used in tests 7C, 7D and 7E. The results of the three tests run at 300 lbs. thrust load and the two tests run at 459 lbs. thrust load are shown in Enclosures 25 and 26 respectively.

From the results of the three tests run at 300 lbs. thrust load it can be seen that experimentally measured films are fairly close to theoretically predicted values. Krytox 143AC lubricant has produced the thickest films of any of the oils tested for any given operating condition. Data are not available at temperatures below 500°F because of the previously noted fast heat-up rate of the bearings with this lubricant. The effects of running-in was also noted in this test series with bearing #8. Film thickness in test 7B were greater, as indicated by the capacitance curves, than in test 7A when the new bearing (#8) was first used. Bearing #8 was inspected after test 7B and was found in good condition. Measurements showed a decrease in surface roughness of the inner and outer rings from 1.4 and 1.8 μ in. to 1.3 and 1.4 μ in. respectively and also of the balls after 1.6 hours of running. This data along with photographs of the tested bearing are given in Enclosure 34.

Bearing #9 was used for test 7C and thicker films were measured by capacitance than in either of the two previous tests 7A and 7B. Conductivity data shows that film thicknesses in all three tests (7A, 7B, 7C) were somewhat similar in the 600° to 700°F range. After running test 7C the thrust load was increased to 459 lbs. and tests 7D and 7E were run. In test 7D, the film thickness/roughness ratio was similar to test 7C. This result appears to be contrary to the previously noted run-in phenomenon where successive tests gave thicker films, however, it follows the load effect seen in test series No.'s 1, 2 and 3 with Mobil XRM-109°F where film thickness/roughness ratios were generally less at higher loads.

Test 7E consisted of approximately 17 hours of running with bearing #9 with film measurements being made continuously during the last 9 hours. The results of these measurements show film thicknesses/roughness ratios much lower than any of the other tests in series No. 7. For about 8 of the hours, films were below the measurable level. After this test, bearing measurements showed increases in surface roughness for both rings and balls (indicating the possible beginning of surface distress). This data along with photographs of the tested bearings are given in Enclosure 35.

Cage speed measurements were made during test 7E with a cage speed measuring system developed in Task 3 and described in (5) and cage speed was found to correspond very well with the theoretically predicted value of 41.99% of inner ring speed as illustrated by the oscillograms of ball passage and inner-ring rotational frequencies as given in Enclosure 39. Cage speed measurements were made continuously for the last eight hours of test 7E for which period h/σ values were less than 2 at 600°F. These results indicate that cage speed is maintained at theoretical value for low h/σ ratios under the load and speed used.

An incidental result of that series No. 7 is the occurrence of a spalling failure in one of the non-test-element support bearings. In this particular instance, a black oxide coated 7205 VAP (M-50 steel) bearing No. 327802, run exclusively in Krytox 143AC fluid, failed after 16.85 hours of operation at 43,000 rpm and 459 lbs. thrust load. The appearance of this failed bearing is shown in Enclosure 38.

The previously used support bearing (no. 327801), similar to the above bearing, suffered a similar spalling failure after 2.6 hours of operation with Krytox 143AC fluid at 300 lbs. (1.7 hours) and then 459 lbs. (0.9 hours) thrust load. This bearing, shown in Enclosure 37 had been run in the previous test series No.'s 5 and 6 with Turbo-S Oil 15 and MCS-354 fluids respectively. Total time on this support bearing, prior to running with the Krytox 143AC fluid, was 19.1 hours at 300 lbs. load at 43,000 rpm.

DISCUSSION - PHASE II

General

It can be seen from the EHD film data that for lubricant films formed by Mobil XRM-109F and Sinclair Turbo-S Oil 15 lubricants the film thickness/roughness ratio falls within the range of $1/2$ to $3/4$ of the isothermal theoretically computed film thickness, whereas the Monsanto MCS-354 polyphenyl ether lubricant gave very thin, almost unmeasurable EHD films with a h/σ ratio generally less than half the theoretical. The results for DuPont Krytox 143AC fluid show h/σ ratios almost equal to the isothermal theoretical with progressive deterioration of h/σ occurring after a few hours of operation due to surface distress in the bearing.

As test speed was lowered, film thickness decreased as expected (20,000 vs 43,000 rpm tests with Mobil XRM-109F) but the film thickness at the lower speed was closer to the theoretical value than at the higher speed. Also, it was found that film thickness tends to decrease as load increases (load series with Mobil XRM-109F at 43,000 rpm).

The difference observed between isothermal theoretical predicted and measured film thickness can be attributed to several factors including:

1. Actual bearing operation at high speeds is anything but isothermal because of the great spinning and shearing heat generation in the contact areas. Since there is considerably less heat generation at 20,000 rpm than at 43,000, it is not surprising that the measured film at the lower speed is closer to theoretical than at the higher speed. Under these conditions theoretical EHD film thickness calculations (23,24) would reduce the discrepancy between theory and experiment (see Supplemental Report, p. 18), but such calculations for all test conditions have not been made.

2. Calculations use fluid properties such as the pressure-viscosity relationship, which is extrapolated from data obtained at much less severe conditions.

3. Interpretation of the electrical measurements of film condition are based on a number of simplifying assumptions and extrapolation of fluid properties data as explained in the Supplemental Report.

4. At high temperatures, even additive-free fluids form deposits on bearing surfaces. These deposits, if insulating, will act to increase measured h/σ in conductivity and, if dielectric, will also be measured into the film thickness by capacitance. This may explain the increasing film thickness at the highest temperature.

a. Mobil XRM-109F

Considerable endurance data has been obtained with Mobil XRM-177F (XRM-109F basestock with additive) at 600°F (2,4,5) and at 700°F in Phase I of this Task. The results of the film measuring studies show that, at the typical endurance test conditions of 43,000 rpm and 459 lbs. thrust load, h/σ values generally range between 1.5 and 3 at 600°F. The lowest of these h/σ values indicate operation in the lower partial EHD region where there are substantial numbers of asperity contacts which may lead to glazing and smearing depending on boundary lubrication conditions. One bearing, run for 41.2 hours at various temperatures in XRM-109F (no additive) showed pronounced

surface distress on the inner ring. Testing with XRM-109F in the earlier program produced smearing failures at short lives (2). On the other hand, tests with XRM-177F ran well and showed little glazing of hard surfaces (WB49 steel) but some glazing for the softer M50 steel. This test behavior correlates well with film measurements which indicate that actual films are considerably less thick than isothermal theoretical calculation suggests so that boundary lubrication provided by an additive package or bearing surface coating is required for long term operation around 600°F of these bearings.

Film measurements around 700°F indicate generally thicker films than at 600°F which does not correlate with testing experience reported in Phase I of this report. Considering that the h/σ values at 700°F are almost and certainly falsified by deposits, this is not too surprising.

b. Sinclair Turbo-S Oil 15

Film measurements with this lubricant show that h/σ ratios no higher than 2.5 are obtained in the 450 to 700°F region. This again indicates operation with numerous asperity contacts which would lead to surface distress in the absence of a boundary lubricating additive. Indeed, in the film measurement runs two bearings run for only a few hours showed severe surface distress. That an additive package can help, is indicated by the qualified success achieved in tests reported in (2) with Turbo-S 1048 at 550°F. Owing to much better film lubrication successful operation was obtained in the temperature region of 700°-750°F in the mainshaft size bearing tests with Turbo-S 1048 having an additive package (1). This, again is to be expected since in the latter tests, $h/\sigma \approx 2$ is likely to exist

As was the case with XRM-109F, there was a peculiar tendency for film thickness to hold constant or increase at the highest test temperatures. This will be discussed in a later section.

c. Monsanto MCS-354

Film measurements with two bearings gave somewhat contradictory quantitative results although qualitatively they agreed that films are below detectable thickness ($h/\sigma \approx 1.5$) above 500°F. This means that glazing (and smearing) can be expected at temperatures above 500°F. This was observed in tests with 7205 bearings and the similar fluid OS-124 reported in (2). It appears that boundary lubrication improvement in the form of additives or bearing coatings is necessary with this fluid for operation above 500°F, at least in an inert atmosphere. It was found in (1) that while Monsanto MCS-293 lubricant (also a polyphenyl ether) smeared in a nitrogen atmosphere at 600°F, it ran successfully in air at the same temperature. It is thought that the oxidation products contributed to the formation of solid lubricating films on the bearing surfaces.

d. DuPont Krytox 143AC

While film measurements with the other lubricants correlated well with previous test experience in that failures could be explained by operation without sufficient lubricant film thickness, measurements with this fluid indicate that at temperatures in the 500-600°F region there should be very few asperity contacts (h/σ around 4), at least during the first few hours of operation. In tests with mainshaft-size bearings (1) this fluid performed well, at least for three hours, at temperatures in excess of 700°F, although there were instances of smearing failures in this temperature range. However, as was pointed out in Phase I of this report, most tests on 7205 bearings with this fluid resulted in very early smearing failures. To explain this observation, a long-term film measurement test (28.9 hours) was run at typical endurance test conditions with Krytox 143AC fluid and the film monitored. This showed that while initially the h/σ ratio was on the order of 4, after a few hours operation the ratio decreased to below 2 and the bearing was found to be surface distressed after disassembly as shown in Enclosure 35. This indicates that even though a rather thick

film exists, progressive surface damage still occurs which will result in failure after a relatively short life. This damage could be due either to chemical attack or to a lack of boundary lubricating ability of this fluid so that occasional asperity contacts cause gross surface deterioration (the fluid attacks and removed the standard black oxide coating in a short time).

Other Effects

a. Detection of Run-In & Onset of Surface Distress

A run-in effect was noted in all instances in which film data were acquired with a new test bearing (test series No's 4,5,6 and 7). It was seen that continued testing with a new bearing resulted in higher h/σ ratios for a given temperature. Measurements on three of the tested bearings showed that they experienced up to a 23% decrease in surface roughness from the new bearing condition. The decrease occurred over a fairly short period of operation as tabulated below.

<u>BEARING</u>	<u>TEST SERIES AND OIL</u>	<u>LOAD (LBS.)</u>	<u>SPEED (RPM)</u>	<u>HOURS</u>	<u>MILL.REVS.</u>	<u>%DECREASE IN SURFACE ROUGHNESS</u>	
						<u>INNER RING</u>	<u>OUTER RING</u>
#3	No. 4 (XRM-109F)	345	20,000	7.6	9.1	12%	23%
#7	No. 6 (MCS-354)	300	43,000	2.8	7.4	3.5%	-5%
#8	No. 7 (KRYTOX 143AC)	300	43,000	1.6	4.1	3.5%	21%

The magnitude of the decrease in rms roughness is misleading. It has previously been found in the SKF Industries' Research Laboratory that a run-in surface has an unsymmetrical asperity distribution with peaks greatly reduced from the original magnitude and valleys intact so that such a surface performs better under partial EHD conditions than its rms roughness would predict.

The remaining test bearings, generally run for longer periods, showed either large increases in surface roughness due to surface distress or wear or were surface distressed to the point of preventing measurements. From the data it appears that new (M-50 steel) 7205 test bearings experience a run-in period during the first few hours of operation (depending on speed) during which time the bearing surface roughness decreases. This phenomenon apparently takes place even in the presence of fairly full EHD films, as was the case with the Krytox 143AC lubricant.

In a condition of substantial asperity interaction progressive deterioration of the bearing raceways occurs in longer operation, particularly in the absence of adequate boundary lubrication as was the case in the film measurement runs performed without additives. This results in an overall increase in surface roughness further increasing asperity contact occurrences leading to further glazing and smearing type failures then supervene as illustrated in Enclosures 27,30,31 and 32.

b. Cause of Increased Film Thickness in 600-700°F Region

It was found in testing with XRM-109F and Turbo-S Oil 15 that measured film thickness increased in the 600-700°F region. Krytox 143AC did not show this tendency and measurements were not taken in this temperature range with MCS-354 due to the low film thickness at lower temperatures. Several possible reasons exist for this including:

1. Formation of surface deposits out of the oil at high temperatures.
2. Increase in viscosity due to thermal degradation, etc.
3. Transfer of polyimide from the cage to rolling elements.

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







If there had been an increase in viscosity during testing it should be detectable by measurement after test. It was found, however, that the viscosity of XRM-109F actually decreased after test. It appears likely that deposits from the lubricants or transfer films from the cage could equally well have caused the increased film thickness which was discernible by both conductivity and capacitance measuring techniques.

CONCLUSIONS

1. 25-mm bore angular-contact WB49 steel ball bearings tested at 700°F under high thrust load and 43,000 rpm speed with inerted Mobil XRM-177F lubricant suffer many more and earlier smearing failures than at 600°F, resulting in a reduction factor of about 15 in estimated bearing smearing life from 600°F to 700°F.
2. Under similar test conditions as in 1., M-50 steel bearings tested at 600°F with DuPont Krytox 143 AC lubricant suffer many more and earlier smearing failures than with Mobil XRM-177F lubricant under the same conditions.
3. Lubricant films at the ball-race contacts in these bearings, sufficiently thick to be detected by conductivity and capacitance techniques, were found with Mobil XRM-109F, Sinclair Turbo-S Oil 15 and DuPont Krytox 143 AC at temperatures up to 700°F, but with Monsanto MCS-354 only up to about 500°F.
4. The measured thickness of the lubricant films in these bearings generally is 1/2 to 3/4 of the computed values according to isothermal elastohydrodynamic theory for XRM-109F and Turbo-S Oil 15, less than 1/2 the theoretical thickness for MCS-354 and about equal to theoretical for Krytox 143 AC.
5. The conductivity film thickness measurement method generally gave higher estimated lubricant film thickness than the capacitance method as used here by a factor not exceeding 2 although the capacitance indicated films were generally thicker in tests with the Krytox 143 AC lubricant and in some tests with another lubricant (XRM-109F) at lower bearing loads. This degree of disagreement is explicable by the difficulty in choice of constants for both methods but may also reflect inherent and unclarified differences in the way these two methods react to the existing film condition. In any event, measurements agree with each other much better than with theory.

6. The frictional heat generated by the bearings used in these lubricant film thickness tests varied greatly with lubricant type. The maximum bearing heat generation resulted in tests with Krytox 143 AC, followed by XRM-109F, MCS-354 and Turbo-S Oil 15 in that order.
8. All bearings used in the lubricant film thickness testing suffered an initial decrease in surface roughness as evidenced by roughness measurements on bearings tested only for short periods followed by lubrication-related surface distress (glazing and superficial pitting) in the ball tracks. This trend was detected by an initial increase in the conductivity-measured film thickness/roughness ratio followed by a gradual decrease in this ratio as the bearing surface condition deteriorated.

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APPENDIX I

LUBRICANT PROPERTIES

MOBIL XRM 109F and 177F LUBRICANTS
(compared with previous lots of XRM 109F base-stock)

Property	XRM 109F (initial lot)	XRM 109F-1 (lot No. 1)	XRM 177F (same as XRM 109F-2)	XRM 109F
Viscosity, cs, at 400°F	4.9	6.5	5.8	5.8
210°F	32.0	43.4	39.8	39.8
100°F	314.1	454.3	442.3	442.6
0°F	-	-	37,610	45,829
-20°F	96,099	-	-	-
-40°F	>99,000	-	-	-
Pour Point, °F	-40	-60	<-35	-
Flash Point, °F	530	450	515	-
Fire Point, °F	580	545	600	-
Autogenous Ignition Point, °F	775	755	830	-
Neutralization No.	-	-	0.11 (0.05 for XRM 109F-2)	-
Bromine No.	-	-	0.1	-
Carbon Residue, %	-	-	< 0.01	-
Volatility, 6-1/2 hrs. @ 500°F, %	15	14.2	-	-
Molecular Weight	-	1,430	-	-
Vapor Pressure, Isoteniscope, Microns at 250°F	-	74	-	-
300°F	-	115	-	-
350°F	-	165	-	-
400°F	-	230	-	-
Dielectric Constant, 1000 cps at 180°F	-	-	-	-
260°F	-	-	-	-
360°F	-	-	-	-
(extrapolated) 600°F	-	-	-	-

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DuPont Krytox-143AC, Lot 1

Engine Lubricant Grade
Krytox-143AC, Lot 1

Appearance	Water White
Pour Point, °F	-30
Density, g/cc	
@ 75°F	1.8996
@ 150°	1.8282
@ 210°F	1.7710
Viscosity, cs.	
@ 25°F	-
@ 0°F	33,035
@ 100°F	276.7
@ 210°F	26.8
@ 400°F	4.1
Viscosity Index	120
ASTM Slope	0.584
Volatility (ASTM D-972 Mod.)	--
6.5 hrs. @ 400°F	11.7
Surface Tension, dynes/cm.	--
Fire Resistance	
Hot Manifold @ 135	--
High Pressure Spray Ignition	--
Autogenous Ignition Temperature	--
Acidity, ppm HF	<1.0
Electrical Properties	
Dielectric Breakdown Voltage, kv	54.0
Dielectric Strength, Volts/mil	540
Volume Resistivity, ohm-cm.	3×10^{15}
Dielectric Constant 10 ⁵ cps	2.11
Dissipation Factor	$<3 \times 10^{-5}$
Loss Factor	$<6 \times 10^{-5}$

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Monsanto OS-124 (Properties as MCS-354)

Viscosity, Density and Compressibility

Temperature °F °C		Viscosity (cs)	Density (g/ml)	Bulk Modulus (psi)
100	38	363	1.19	390,000
210	99	13.1	1.14	320,000
400	204	2.1	1.06	215,000
500	260	1.2	1.01	180,000
600	316	0.85	0.97	145,000 (est.)
700	370	0.65	0.93	-

Pour Point +40°F (5°C)

Vapor Pressure

12 mm Hg at 650°F (343°C)
100 mm Hg at 800°F (427°C)
760 mm Hg at 982°F (530°C)

Evaporation Loss (ASTM D-972)

6-1/2 hours at 500°F (260°C)
at 140 mm 8% maximum
at 760 mm 4% maximum

Heat Transfer Properties

Temperature °F °C		Specific Heat (BTU/lb °F)	Thermal Conductivity (BTU/°F, ft/hr)
100	38	0.368	0.0768
300	150	0.432	0.0702
500	260	0.496	0.0642 (ext.)
700	370	0.560	0.0582 (ext.)

Flammability Properties

Flash Point 550°F (288°C)
Fire Point 660°F (350°C)
Autogenous Ignition
Temperature 1135°F (557°C)*

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Sinclair Turbo S-Oil 15

<u>Viscosity</u>	65°F	12,106
	100°F	16.75
	210°F	4.28
<u>Pour Point</u>	80°F	
<u>Flash Point</u>	450°	
<u>Fire Point</u>	495°	
<u>Autogenous Ignition</u> <u>Point</u>	750° (approx.)	

Neut. No. .12

Vol. 6-1/2 hrs. @ 400°F 10.5%

APPENDIX II

SAMPLE CALCULATION OF BEARING σ VALUE

Sample Calculation of Bearing σ Value
(for Bearing #1, 327701)

1. The surface roughness of the bearing rolling elements is measured in microinches A.A. (Arithmetic Average) and then converted to microinches rms. through multiplication by a correction factor of 1.1.

	Inner Ring	Outer Ring	Balls
microinches A.A.	1.51	1.90	1.60
microinches rms	1.66	2.09	1.76

2. The rms roughness of the two rings is averaged

$$\sigma_1 = \sqrt{\frac{(\sigma_{\text{inner}})^2 + (\sigma_{\text{outer}})^2}{2}}$$

$$\sigma_1 = \sqrt{\frac{(1.66)^2 + (2.09)^2}{2}}$$

$$\sigma_1 = 1.88$$

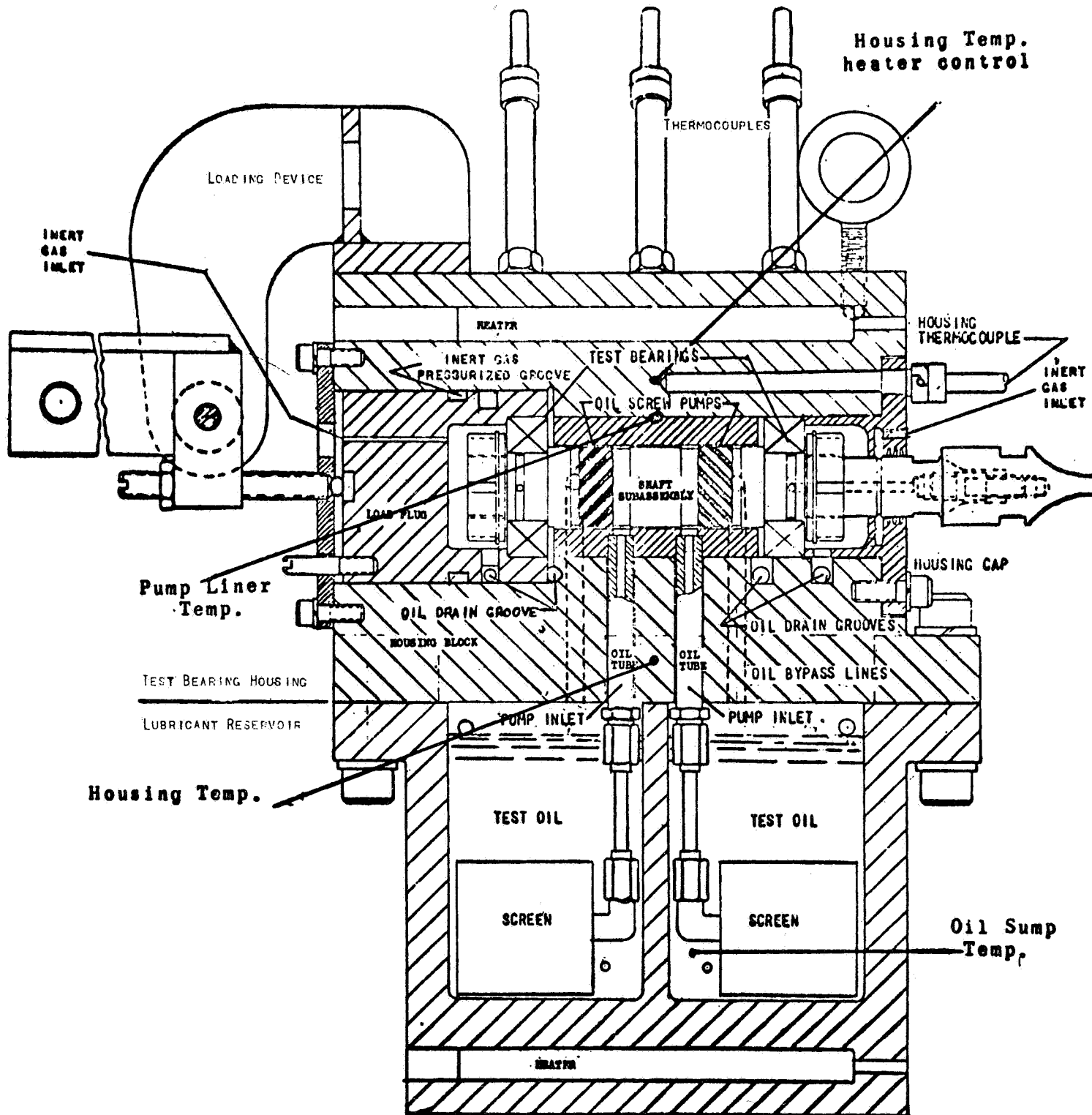
3. σ (bearing) is then computed as follows

$$\sigma = \sqrt{\sigma_1^2 + (\sigma_{\text{ball}})^2}$$

$$\sigma = \sqrt{(1.88)^2 + (1.76)^2}$$

$$\sigma = 2.58 \mu'' \text{ rms}$$

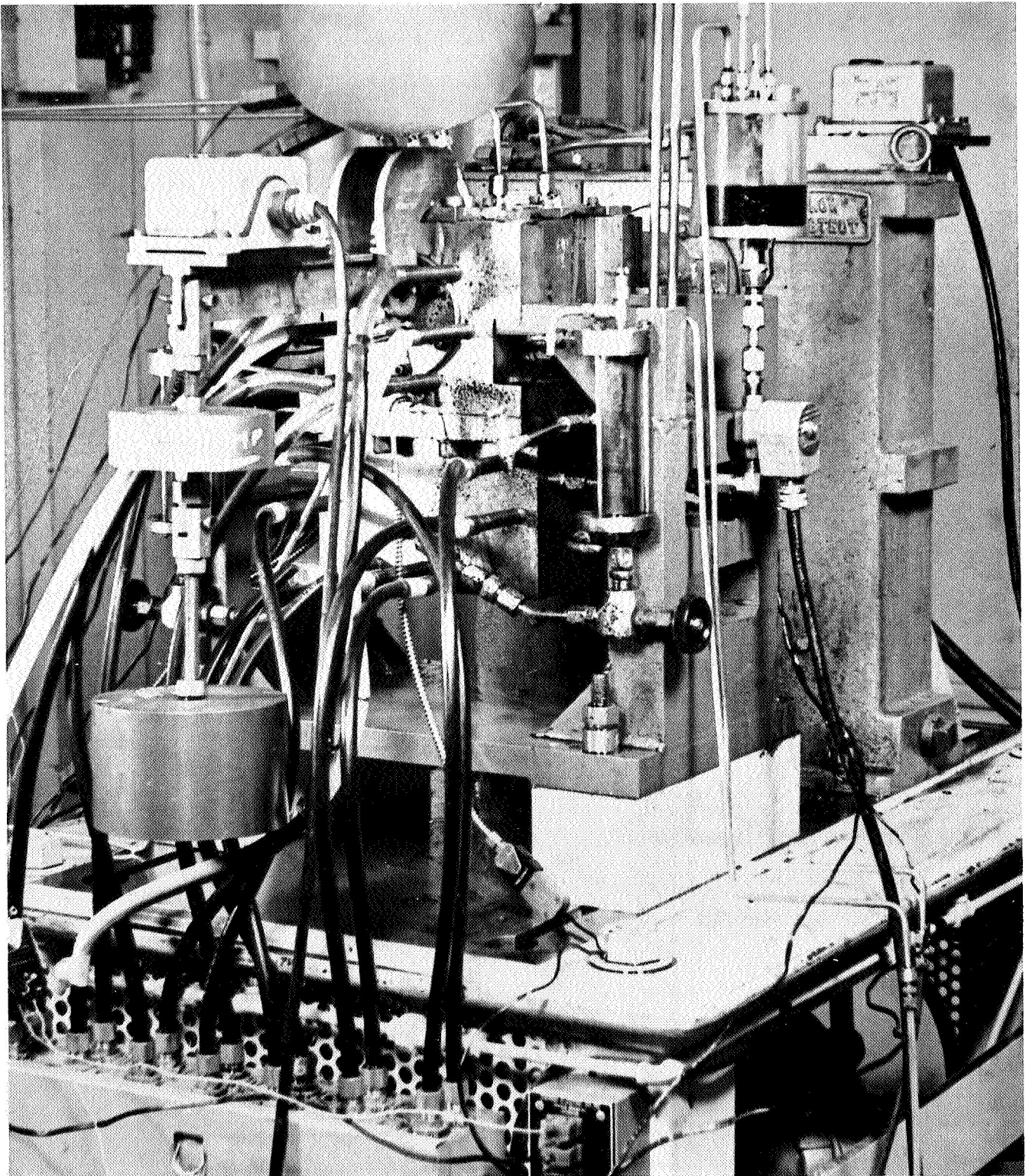
ENCLOSURE 1

LAYOUT SKETCH OF HIGH-SPEED HIGH-TEMPERATURE TEST RIG

AL68T005

ENCLOSURE 2

HIGH-SPEED HIGH-TEMPERATURE BEARING TEST MACHINE



RESEARCH LABORATORY **SKF** INDUSTRIES, INC.

ENCLOSURE 3

VARIABLE-SPEED TEST RIG CONTROL PANEL

HEATERS - MOTOR
ON
OFF

LOW, HIGH PRESS.
INDICATORS RESET

SPEED-AMPS-VOLTS-HOUR METER

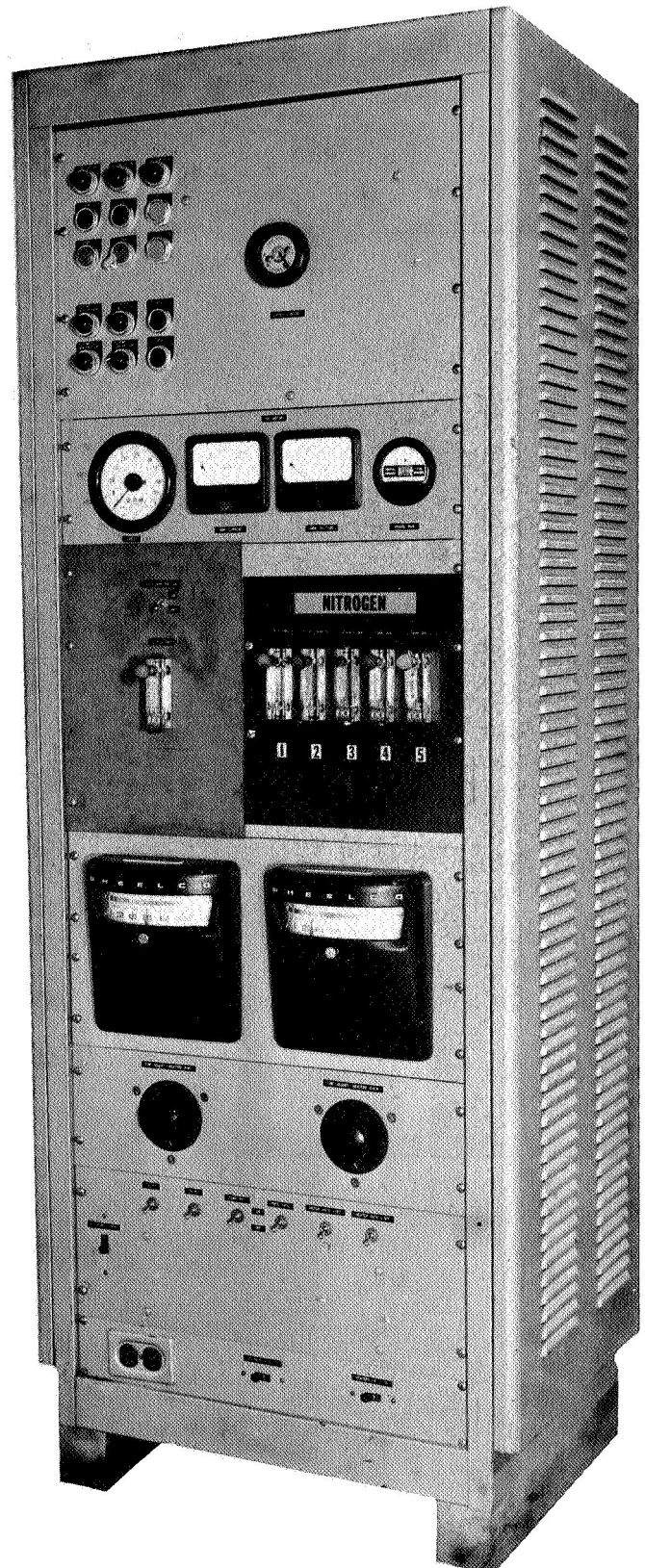
N₂ PURGE METERS

HEATER CONTROLS
1-7 8-14

FINE ADJUSTMENT
HEATERS
6-7 13-14

INSTRUMENT SWITCHES

HEATER SWITCHES



ENCLOSURE 4

COMPOSITION AND HOT HARDNESS
CHARACTERISTICS OF HIGH-TEMPERATURE BEARING STEELS

	<u>M-50</u>	<u>M-1</u>	<u>WB-49</u>
<u>Elemental Composition, %:</u>			
C	.77- .85	.75- .85	1.00-1.10
Mn	0.35 max.	0.15-0.40	0.20-0.40
Si	0.25 max.	0.15-0.40	0.20-0.40
Cr	3.75-4.25	3.5 -4.25	4.00-4.50
P	0.015 max.	0.015 max.	0.015 max.
S	0.015 max.	0.015 max.	0.015 max.
Ni	0.10 max.	0.10 max.	0.10 max.
Cu	0.10 max.	0.10 max.	0.10 max.
Mo	4.00-4.50	8.45-9.25	3.50-4.00
W	0.25 max.	1.40-2.00	6.50-7.00
V	0.90-1.10	1.00-1.20	1.80-2.10
Co	0.25 max.	-	5.00-5.55

Hard Hardness After
 Long-Term Soaking at
Temperature (13-16) RC:

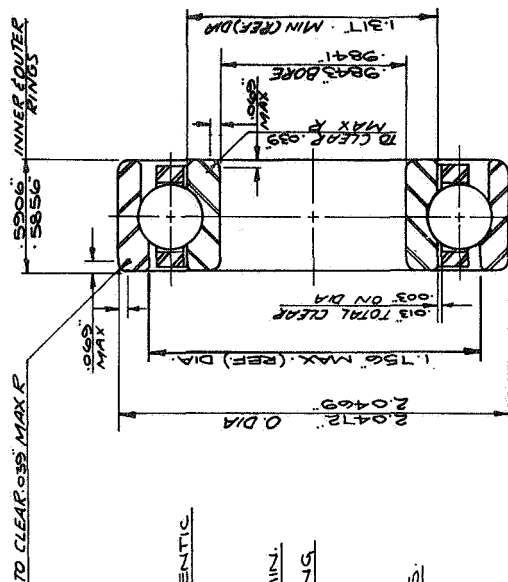
Room Temp.	64	66	69
400°F	61	62	-
600°F	57	60	65
800°F	55	57	62
1000°F	46	52	57

Hardness Measurements
 on 7205 VAG (M-50
Steel) Parts, Rc:

<u>Inner Rings</u>	<u>Outer Rings</u>	<u>Balls</u>
62	62	64

ENCLOSURE 5

7205 VAR. TEST BEARING

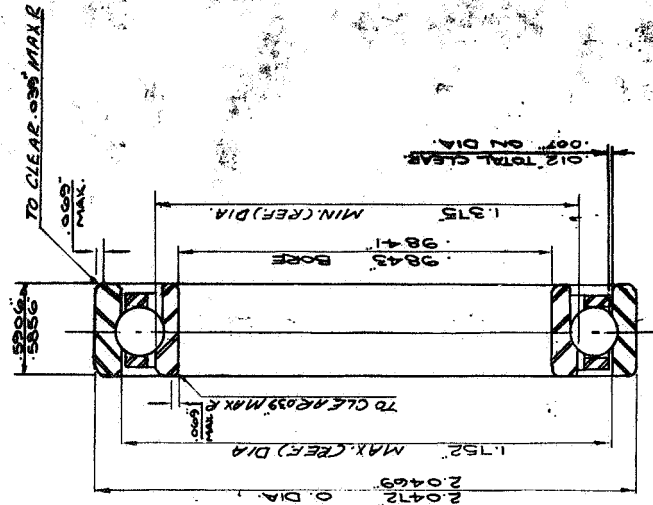


7205 VAR

[illegible]

1. INNER AND OUTER RINGS TO BE MADE FROM V849 STEEL, HARDNESS RC 64 TO 69, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENITIC GRAIN SIZE 10 MIN. PER SNYDER - GRAFF INTERCEPT METHOD.
2. BALLS TO BE MADE FROM M-1 STEEL, HARDNESS RC 62 TO 65, RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENITIC GRAIN SIZE 10 MIN. PER SNYDER - GRAFF INTERCEPT METHOD.
3. CAGE TO BE MADE SILVER PLATED M-1 STEEL, HARDNESS RC 55 MIN. ONE PIECE MACHINED INNER LAND RIDING.
4. GROOVE CONFORMITIES TO BE 52.5% NOM FOR THE INNER RING AND 53.2% NOM FOR THE OUTER RING.
5. SHOULDER HEIGHTS TO BE 15.5 - 15.8% FOR THE INNER RING AND 15.8 - 17.1% FOR THE OUTER RING.
6. CROSS GROOVE SURFACE ROUGHNESS TO BE 4 MICROINCHES RMS MAX. FOR BOTH INNER AND OUTER RINGS. SURFACE ROUGHNESS TO BE 1.2 MICROINCHES RMS MAX. FOR THE BALLS.

 GKF INDUSTRIES, INC. 7000 WEST 100th AVE. DALLAS, TEXAS 75243		DRAWING CHECK APPR. REC. T.M.K. 677814 <i>6/14/66</i> DATE 6-14-66 SCALE 1"=1'-0"	
BRG. N2 7205 VAR		7205 VAR	



BEARING DATA	
VENDOR'S PART N°	S K F
VENDOR'S DRAWING N°	T205 VAP
BEARING TOLERANCE	T205 VAP
N° 8 SIZE OF BALLS	ABEC5
INTERNAL RADIAL LOOSENESS (TOTAL)	12-3175" DIA.
TYPE OF BEARING	.0020" .0024"
DESIGN CONTACT ANGLE	ANGULAR CONTACT
PITCH DIA. (NOMINAL)	24°
CAGE WIDTH	1.541
	.555

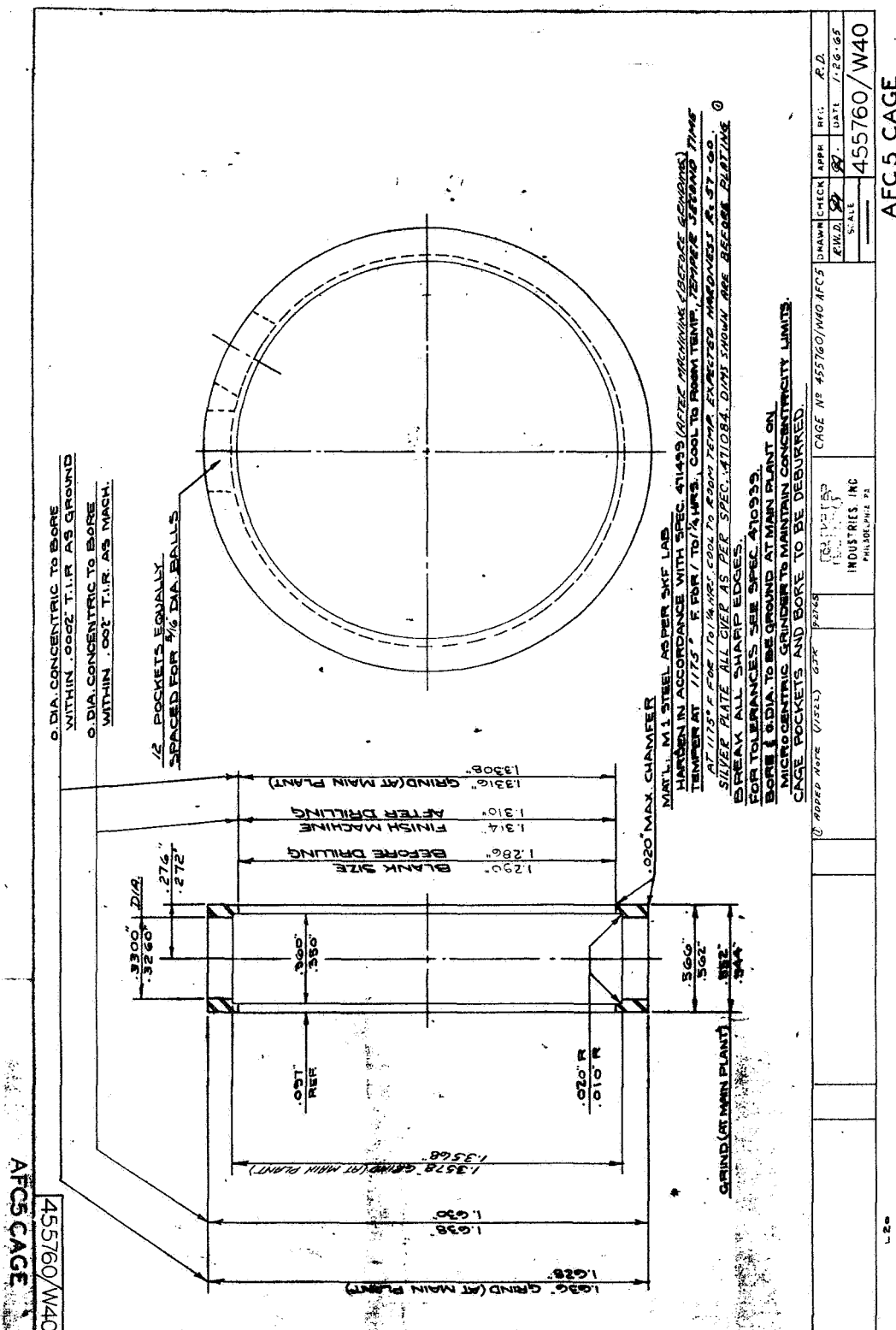
1. 1. INNER AND OUTER RINGS TO BE MADE FROM M-50 STEEL, HARDNESS. NOM. RC 62. RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENITIC GRAIN SIZE 7 MIN. PER SNYDER- GRAFF INTERCEPT METHOD.
2. BALLS TO BE MADE FROM M-50 STEEL HARDNESS NOM. RC 62. RETAINED AUSTENITE CONTENT NOT TO EXCEED 3% AUSTENITIC GRAIN SIZE 7 MIN. PER SNYDER- GRAFF INTERCEPT METHOD.
3. CAGE TO BE MADE FROM SILVER PLATED M-1 STEEL HARDNESS. RC 55 MIN. ONE PIECE MACHINED, OUTER LAND RISING.
4. GROOVE CONFORMITIES TO BE .52.3 % NOM. FOR INNER RING AND .52.8 % NOM. FOR OUTER RING
5. SHOULDER HEIGHTS TO BE 24.8 - 26.2 % FOR THE INNER RING AND 16.5 - 16.9 % FOR THE OUTER RING.
6. CROSS GROOVE SURFACE ROUGHNESS TO BE 4 MICRO-INCHES RMS MAX. FOR BOTH INNER AND OUTER RINGS. SURFACE ROUGHNESS TO BE 1.2 MICRO-INCHES RMS MAX. FOR THE BALLS.
7. INNER AND OUTER RINGS TO BE BLACK OXIDE COATED PER AMS 2483

DRAWN		CHECK	APPR.	RES.
DATE		DATE		
SCALE		7205 VAP		

BRG N2 7205 VAP

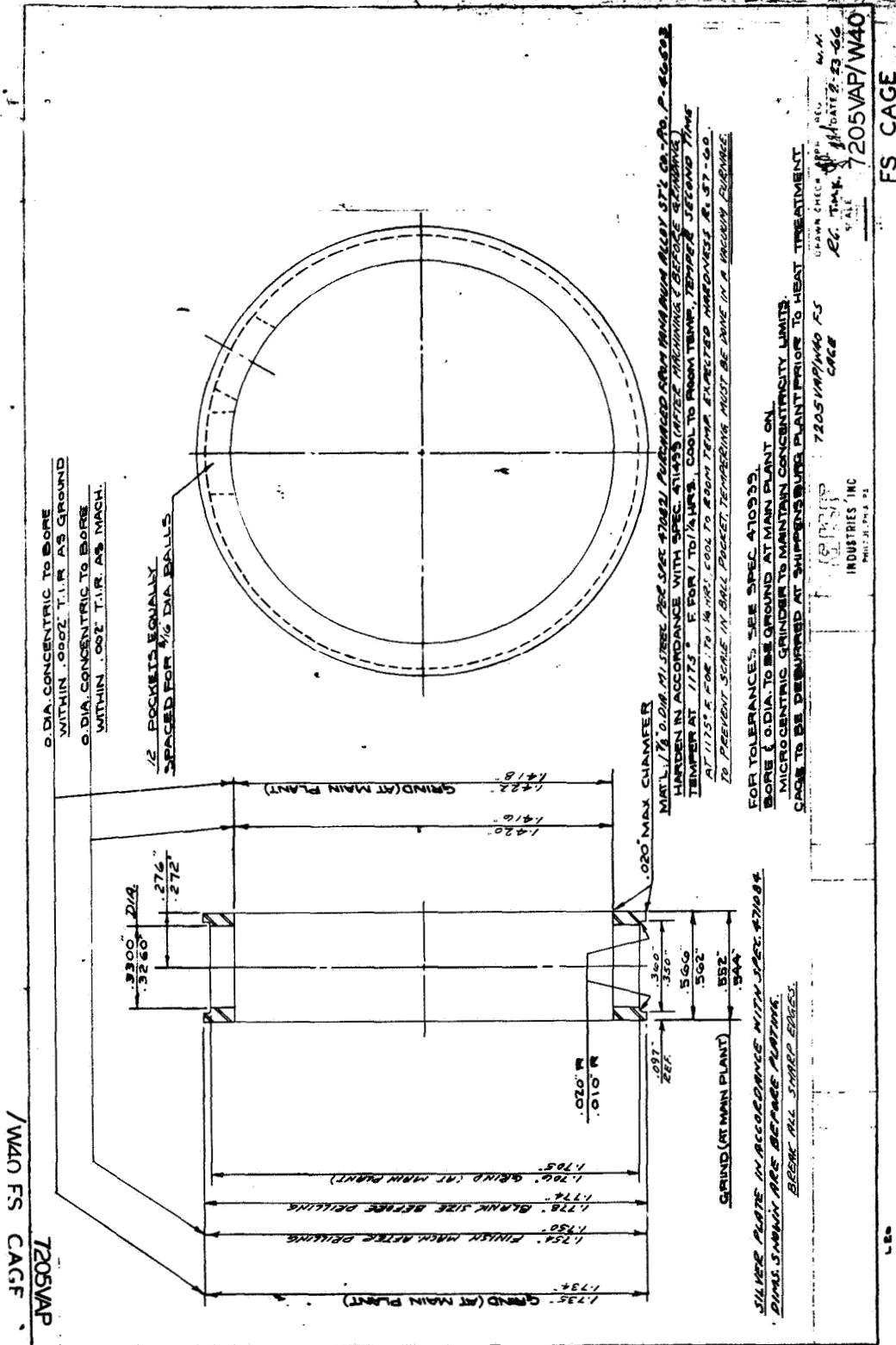
INDUSTRIES, INC.
 10000 100th Ave. N.E.
 Redmond, WA 98073

7205 VAR TEST BEARING CAGE (INNER RING GUIDED)



ENCLOSURE 8

7205 VAP TEST BEARING CAGE (OUTER RING GUIDED)



ENCLOSURE 9

TRACE ELEMENT ANALYSIS OF CVM M-50 STEELElemental Analysis w/o

<u>CVM M-50 Heat Identification</u>	<u>Al</u>	<u>Cu</u>	<u>Ni</u>	<u>Trace Element Index*</u>
7205 VAG rings	0.03	0.03	0.07	3.5
7205 VAP bearings**	0.03	0.04	0.04	3.2
Bearings with above-average life:				
Heat No. 1	0.03	0.09	0.06	4.2
Heat No. 2	0.03	0.09	0.06	4.2
Bearings with below-average life:***	0.05	0.08	0.15	6.8

* The trace element index (θ) developed for 52100 steel (14) has been adapted for M-50 steel as follows:

$$\theta = \frac{\text{Al}}{0.015} + \frac{\text{Cu}}{0.06} + \frac{\text{Ni}}{0.07}$$

** New test bearings made for this program as reported in (4).

*** In a previous test on a small group of bearings made of CVM M-50 steel on a NASA subcontract let by Aerojet General Corp. (Azusa P. O. OP367915 on Contract NAS5-417), the estimated L_{10} = 26 million revolutions compared to the log average L_{10} = 85 million revolutions for groups of similar bearings made of five heats of CVM M-50 steel tested under the same conditions in the SKF Industries' Research Laboratory.

ENCLOSURE 10

7205 VAR AND 7205 VAP TEST BEARING DIMENSIONAL MEASUREMENTS

Bearing	Match No.	Outside Diameter (mm)	Bore Diameter (mm)	Contact Angle (degrees)	Radial Looseness (Microns)	Groove Rading (mm)		Taper(microns)		Out Of Round(Microns)		Surface Roughness (Micro-inches, A.A.)	
						Inner	Outer	Inner	Outer	Inner	Outer	Inner	Outer
7205 VAR													
1. 327101	232	52.0005	24.99825	15.3	51	4.167	4.230	0.5	1.0	2.0	2.0		
2. 327102	234	52.0000	24.99775	15.3	42	4.167	4.203	0.5	1.0	2.0	3.0		
3. 327103	233	51.99625	24.99725	13.3	42	4.162	4.204	0.5	0.5	1.0	3.0		
4. 327104	207	51.99675	24.99625	14.8	45	4.149	4.242	0.5	0.5	2.0	5.0		
5. 327105	246	52.00025	24.99725	13.3	49	4.140	4.204	0.5	1.5	2.0	3.0		
6. 327106	247	52.0000	24.99675	14.8	43	4.159	4.235	0.5	0.0	2.0	2.0		
7. 327107	277	51.996	24.99775	13.3	40	4.153	4.230	0.5	0.0	1.0	2.0		
8. 327108	288	51.9985	24.99725	13.3	40	4.158	4.226	1.5	1.0	1.0	2.0		
9. 327109	272	51.99675	24.99975	15.9	43	4.157	4.206	1.5	1.5	2.0	2.0		
10. 327110	283	51.998	24.9985	12.7	44	4.157	4.247	2.0	6.0	1.0	4.0		
11. 327201	267	51.9965	24.997	13.3	39	4.150	4.221	0.0	1.0	1.0	4.0		
12. 327202	268	51.99525	24.99875	16.4	52	4.160	4.222	0.5	0.5	2.0	3.0		
13. 343101	249	51.99875	24.997	13.3	44	4.151	4.226	1.0	1.5	1.0	2.0		
14. 343102	270												
15. 327301	704	51.999	24.997	15.3	47		4.239	0.0	1.0	2.0	3.0		
16. 327302	691	51.99475	24.99775	14.0	40		4.228	0.5	0.5	1.0	3.0		
17. 327601													
18. 327602													
7205 VAP*													
1. 327401	7	51.9965	24.99825	23.0	57	4.187	4.171	0.75	0.0	0.5	1.0		
2. 327402	14	51.9995	24.99825	25.6	57	4.221	4.181	0.5	0.0	0.5	1.0		
3. 327403	10	51.998	24.9985	24.6	55	4.223	4.176	1.0	1.0	1.0	1.0	1.53	1.95
4. 327404	18	51.9965	24.99925	26.0	59	4.212	4.178	0.5	0.0	1.0	1.0		
5. 327501	16	51.997	24.998	24.2	59	4.228	4.172	0.5	1.0	0.5	1.0	1.38	3.16
6. 327502	20	51.9945	24.9995	22.2	52	4.210	4.200	0.5	0.0	0.5	1.0	1.43	1.85
7. 327503	25	51.9965	24.999	24.5	55	4.195	4.170	0.5	1.0	0.5	2.0	1.50	1.73
8. 327504	34	51.994	24.99875	23.0	59	4.214	4.169	0.25	0.0	0.5	1.0	1.50	1.71
9. 327505	21	51.996	24.99875	23.1	55	4.211	4.200	0.5	1.0	1.0	1.0		
10. 327506	30	51.997	24.997	24.4	50	4.231	4.176	1.25	1.0	1.0	1.0	1.51	1.90
11. 327701	33	51.997	24.99875	23.1	51	4.222	4.175	0.5	1.0	1.0	1.0	1.46	1.85
12. 327702	203			23.0	69	4.221	4.188					1.36	1.83
13. 327703	197			23.4	59	4.198	4.179					1.41	1.95
14. 327704	105			24.1	64	4.202	4.179					1.38	1.75
15. 327705	137			23.7	61	4.206	4.186					1.45	1.71
16. 327706	31	51.99625	24.99825	22.0	45	4.226	4.184	0.5	0.5	1.0	2.0	1.45	1.55
17. 327707	208			24.1	57	4.219	4.177					1.41	1.78
18. 327708	55			23.8	51	4.213	4.187					1.38	1.43
19. 327709	205			23.8	68	4.226	4.206					1.38	1.43
20. 327801	35	51.9955	24.999	22.0	59	4.212	4.194	0.5	0.0	0.5	1.0		
21. 327802	43			22.0	56	4.230	4.191						

* Five additional 7205 VAP bearings were used on this Task for preliminary set up and check out of the film measuring system and endurance rigs. Since no test results are reported for these 5 bearings, no measurements are given.

ENCLOSURE 11

SUMMARY OF 7205 VAR ENDURANCE TESTS AT 700°F
43,000 RPM SPEED WITH MOBIL XRM-177F LUBRICANT

TEST NO.	BEARINGS	LOAD (LBS)	LIFE		RESULTS
			(hrs.)	(Mill.Revs.)	
1.	(1)* 327101 (d) 327102	459	44.3	115.9	Smeared Spalled Balls
2.	(1) 327103 (d) 327104	459	41.7	109.1	Smeared Debris Dented
3.	(1) 327105 (d) 327106	459	19.2	50.2	Surface Distress Smeared
4.	(1) 327107 (d) 327108	459	6.3	16.5	Debris Dented Smeared
5.	(1) 327109 (d) 327110	459	31.5	83.4	Smeared Debris Dented
6.	(1) 327201 (d) 327202	200	7.0	13.8	Smeared Debris Dented
7.	(1) 343101 tungsten disulfide coated (d) 343102 "	459	156.5	409.4	Debris Dented Fatigue Spall
8.	(1) 327301 " (d) 327302 "	459	10.8	28.2	Smeared Debris Dented
9.	(1) 327601 inc. cage clearance** (d) 327602 "	459	46.3	121.3	Debris Dented Smeared

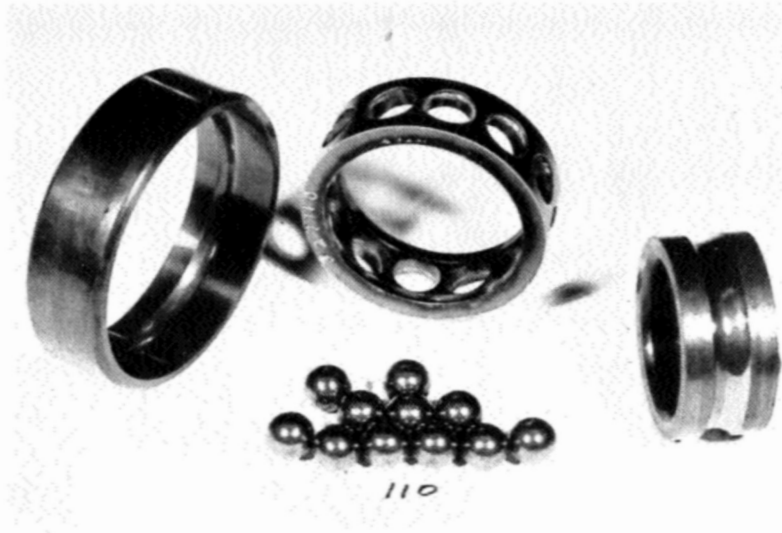
*(1) denotes load end bearing

(d) denotes drive end bearing

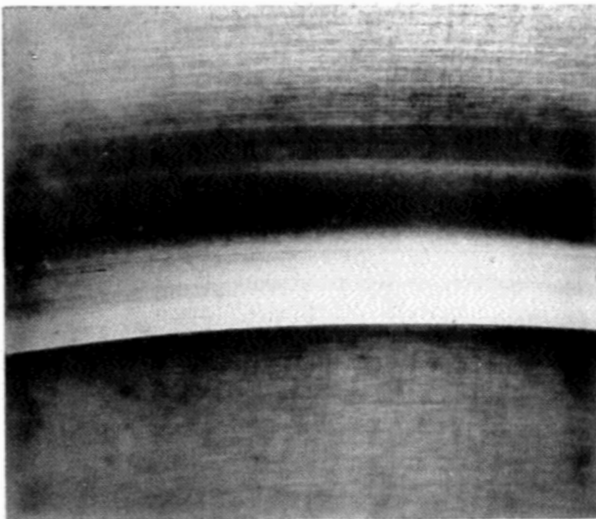
** Cage clearance increased from 0.008" to 0.016" (diametral)

ENCLOSURE 12

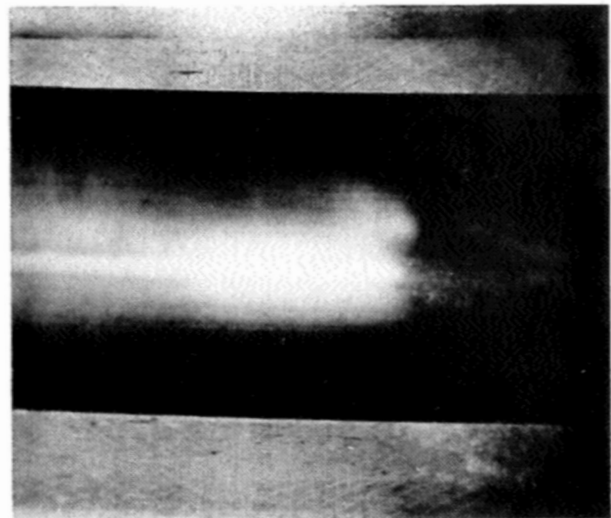
Typical Appearance of Unfailed 7205 VAR Test Bearing After
700°F Operation with Mobil XRM-177F Lubricant



Test Bearing No. 327110

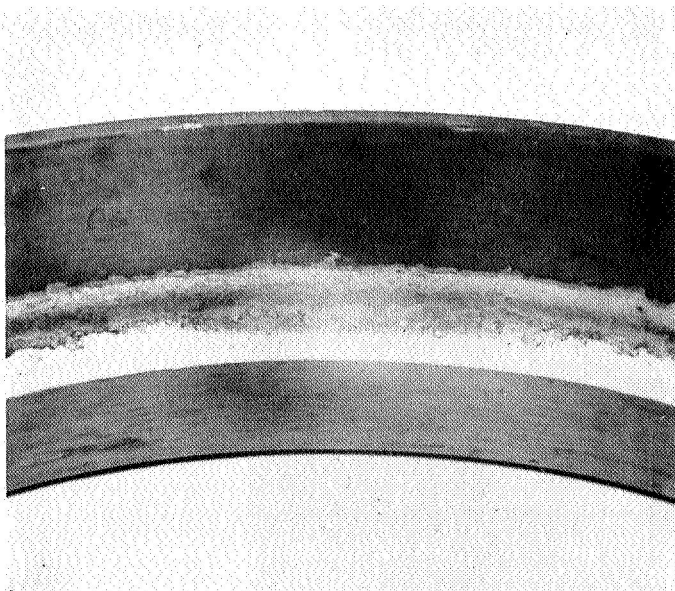
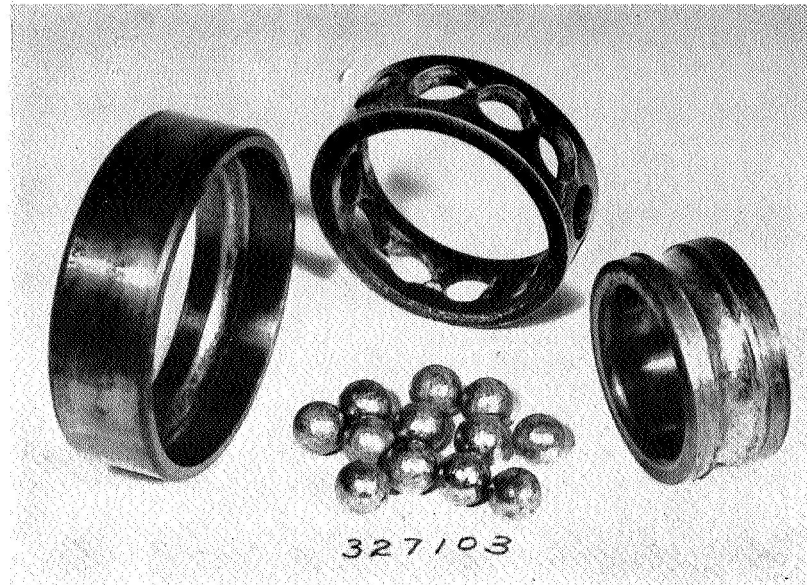


Outer Ring Raceway

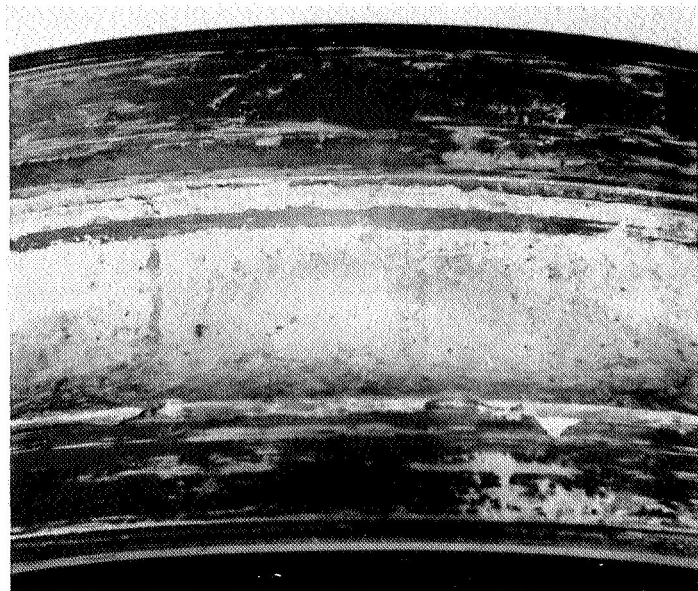


Inner Ring Raceway

Typical Appearance of Smeared 7205 VAR (WB49 Steel) Bearing

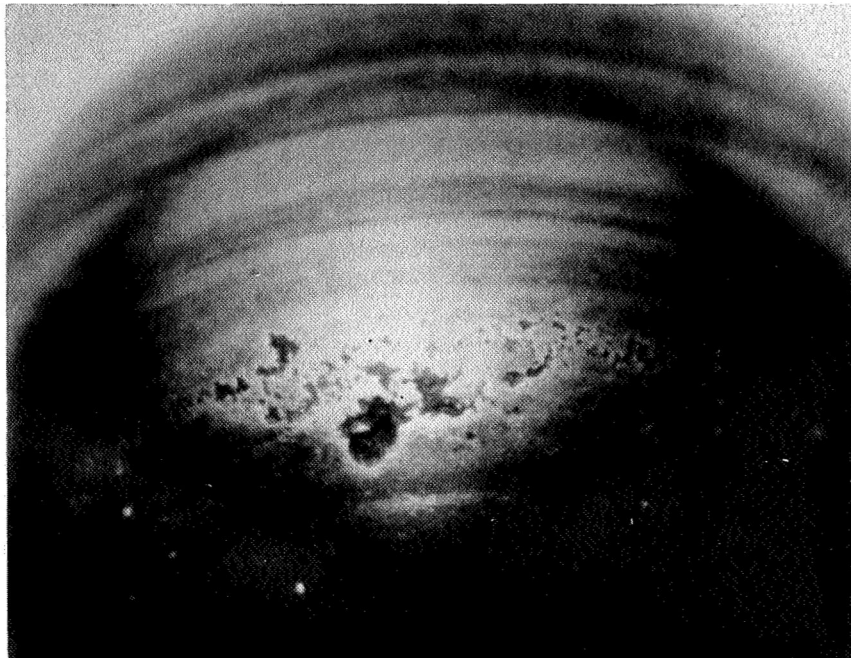
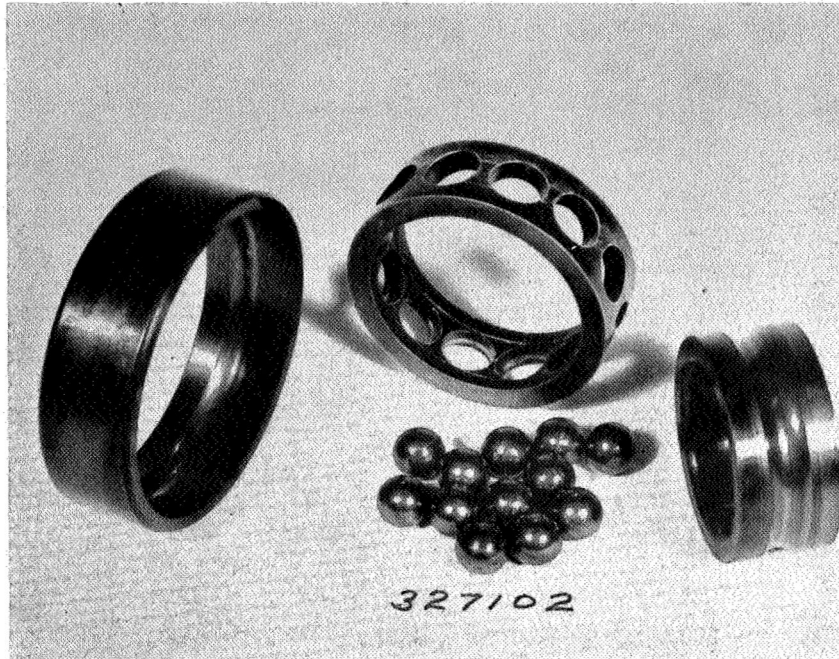


Outer Ring



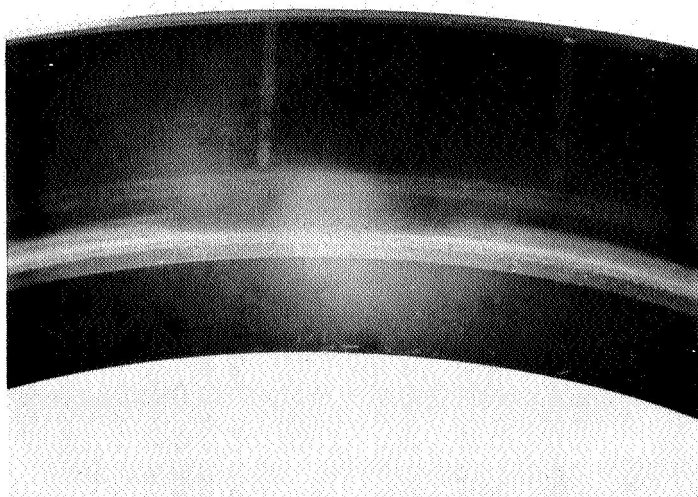
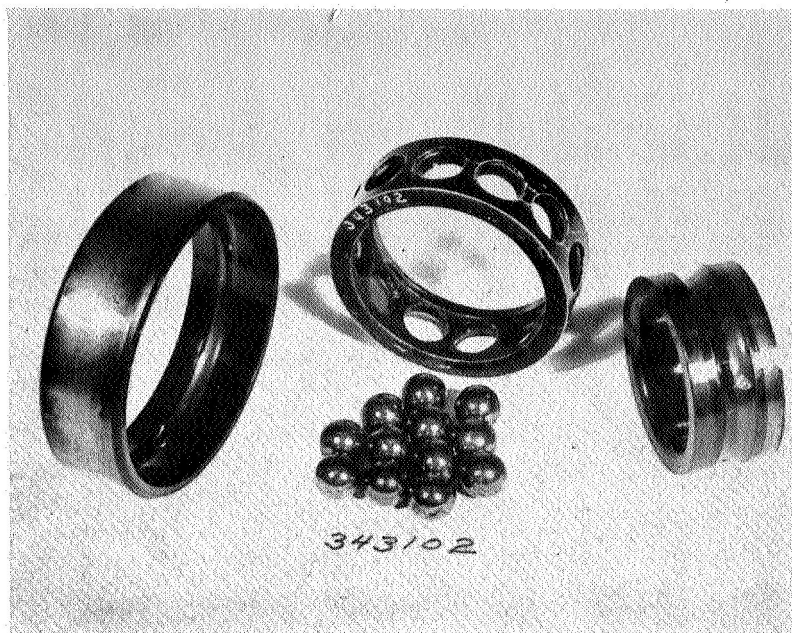
Inner Ring

Appearance of 7205 VAR Bearing With Spalled Balls After
44.3 Hours of Operation at 700°F

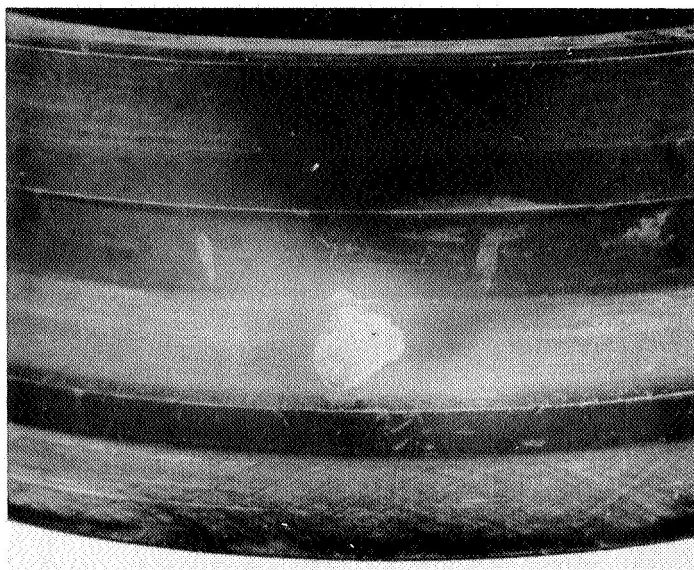


ENCLOSURE 15

Appearance of 7205 VAR Bearing (Having a Proprietary Tungsten Disulfide Surface Coating) Which Suffered a Spalling Fatigue Failure After 156.5 Hours of Operation at 700°F



Outer Ring



Inner Ring

ENCLOSURE 16

Summary of 7205 VAP (M-50 Steel) Endurance
Tests with DuPont Krytox 143 AC

TEST NO.	BEARINGS		TEST RIG	START UP PROCEDURE	RESULTS	
1.	(1) 324701	7205VAP	Monel	High Speed	Drive end bearing smeared on start-up	
	(d) 327402	7205VAP				
2.	(1) 327403	7205VAP	Monel	High Speed	Drive end bearing smeared on start-up	
	(d) 327404	7205VAP				
3.	(1) 327501	7205VAP, coated*	Monel	High Speed	Drive end bearing smeared on start-up	
	(d) 327502	7205VAP, coated				
4.	(1) 327503	7205VAP, coated	Monel	Slow Speed	Drive end bearing smeared 0.4 hrs. after start-up	
	(d) 327504	7205VAP, coated				
5.	(1) 327503	7205VAP, used*	Monel	Slow Speed	Drive end bearing smeared 1.1 hrs. after start-up	
	(d) 327501	7205VAP, used				
6.	(1) 194106	7205VAG, used, coated	Monel	Slow Speed	Drive end bearing spalled 1.2 hrs. after start-up	
	(d) 194107	7205VAG, used, coated				
7.	(1) 327505	7205VAP, coated	Monel	Slow Speed	Drive end bearing smeared 0.3 hrs. after start-up	
	(d) 327506	7205VAP, coated				
8.	(1) 327401	7205VAP, used	Stainless	Slow Speed	No failure after 0.5 hours	
	(d) 194121	7205VAG, used, coated				
9.	Same as 8		Stainless	High Speed	Drive end bearing smeared on start-up	
10.	(1) 327401	7205VAP, used	Stainless	Slow Speed	Drive end bearing spalled after 6.4 hours	
	(d) 194106	7205VAG, used, coated				
11.	(1) 327401	7205VAP, used	Stainless	Slow Speed	Drive end bearing smeared on start-up	
	(d) 327503	7205VAP, used, coated				
12.	(1) 327401	7205VAP, used	Stainless	Slow Speed	Drive end bearing smeared 0.1 hrs. after start-up	
	(d) 194127	7205VAP, used, coated				
13.	(1) 327401	7205VAP, used	Stainless	Slow Speed	Drive end bearing smeared after 8 hours	
	(d) 327505	7205VAP, used, coated				

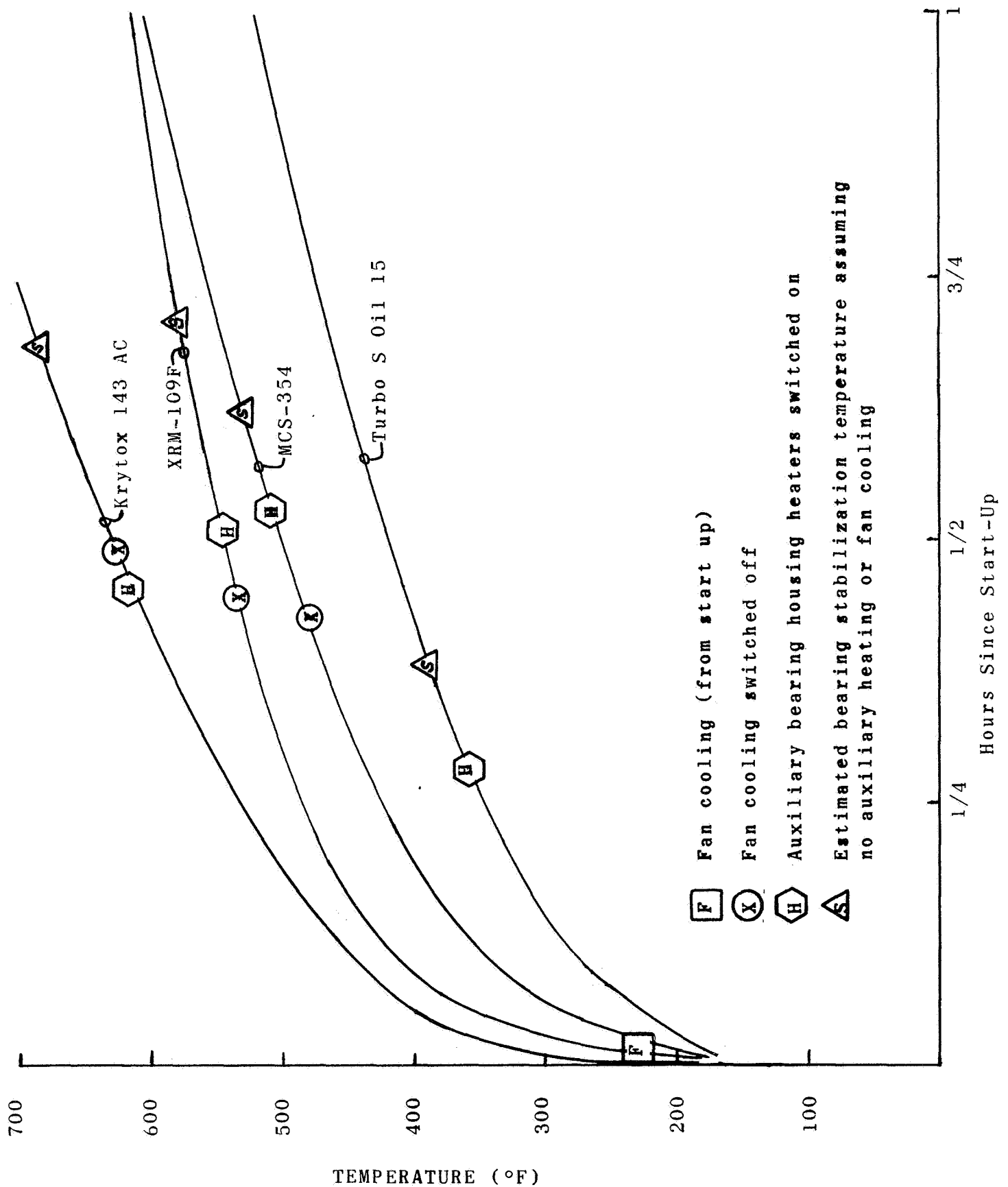
- NOTES: 1.* "Coated" refers to a black oxide boundary lubrication surface coating: "used" denotes that bearings were in previous testing (see also note 3).
2. Test No.'s 6 through 13 were run with modified housing alignment procedure as described in text.
3. Used 7205VAG bearings are from a group of 30 M50 steel bearings described and tested in (9).
4. Two additional 7205VAP bearings were damaged during assembly and for this reason were not used in any of the above tests.
5. (1) load end bearing; (d) drive end bearing.

ENCLOSURE 17

Load-End Vs. Drive-End Smearing Failures to Date

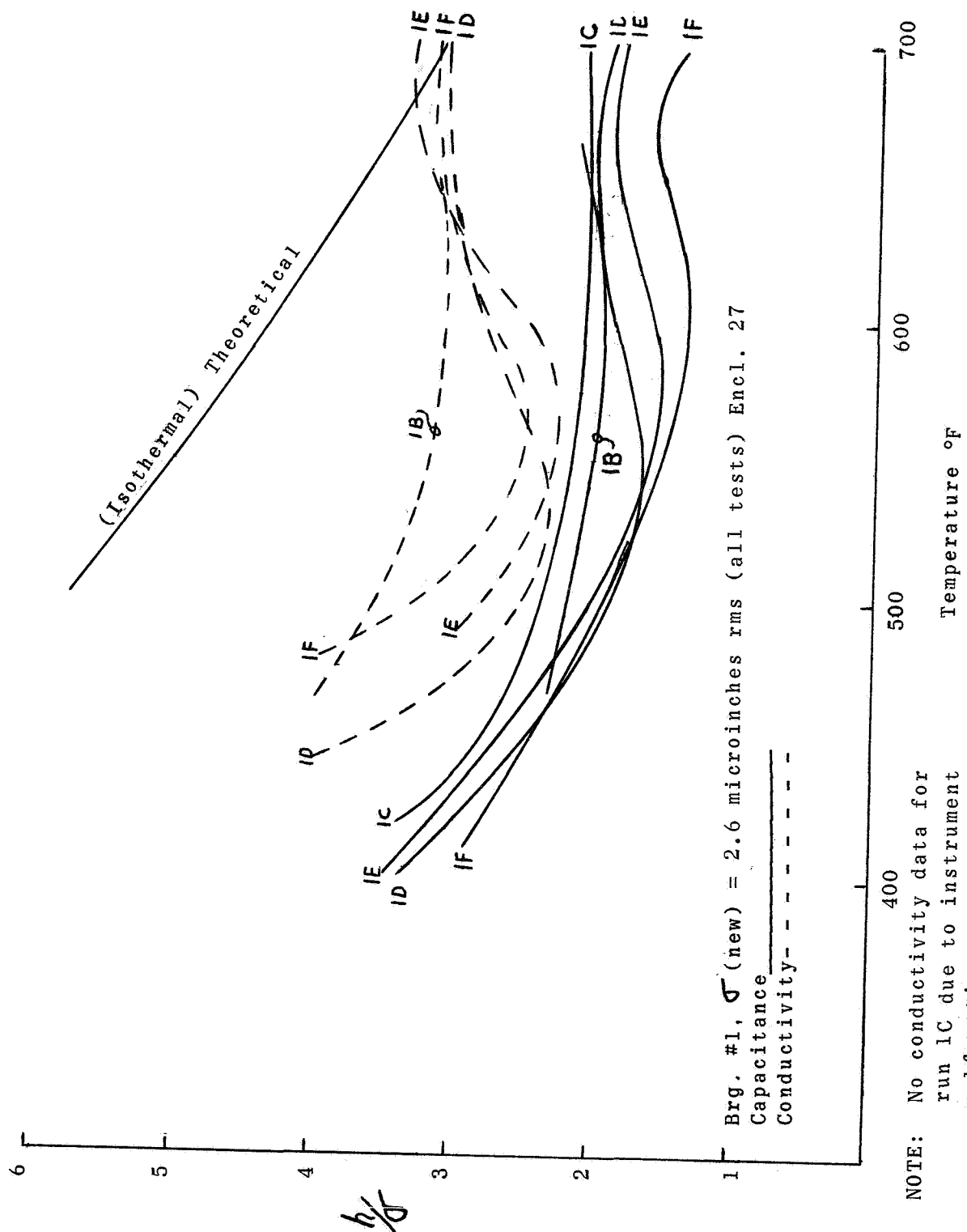
<u>Program</u>	<u>Test ≤</u> <u>1 hr. Duration</u>		<u>Test ≥</u> <u>1 hr. Duration</u>	
	<u>Drive End</u>	<u>Load End</u>	<u>Drive End</u>	<u>Load End</u>
NASw-492	32	23	15	16
NAS3-7912, Task 2	3	2	4	1
Task 3	-	-	1	-
Task 5	9	-	4	5
Total to Date	44	25	24	22

ENCLOSURE 18
Relative 7205 Bearing Heat-Up
Rate With Film Measuring Lubricants



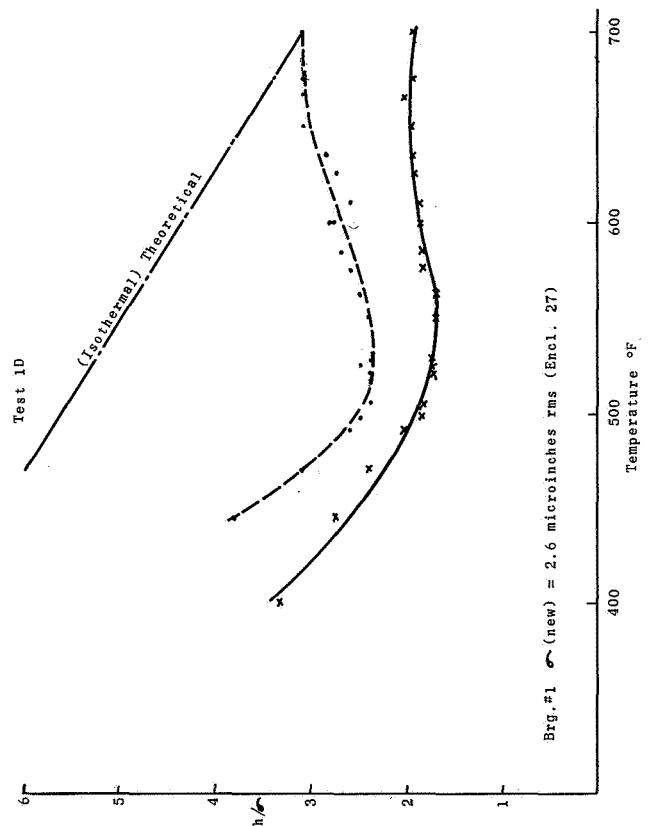
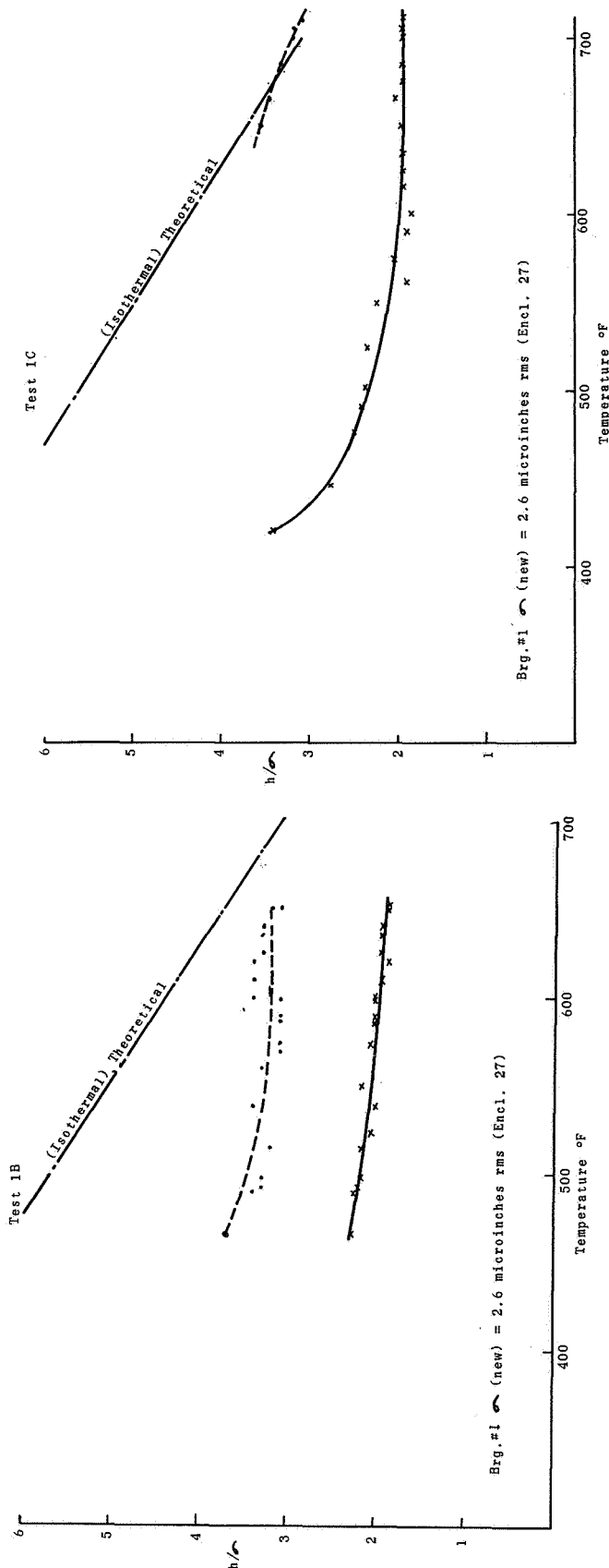
ENCLOSURE 19A

Composite Plots of Lubricant Film Condition Vs. Bearing
Temperature for Test Series No.1, Lubricant-Mobil XRM-109F,
Speed - 43,000 rpm, Thrust Load - 459 Lbs.



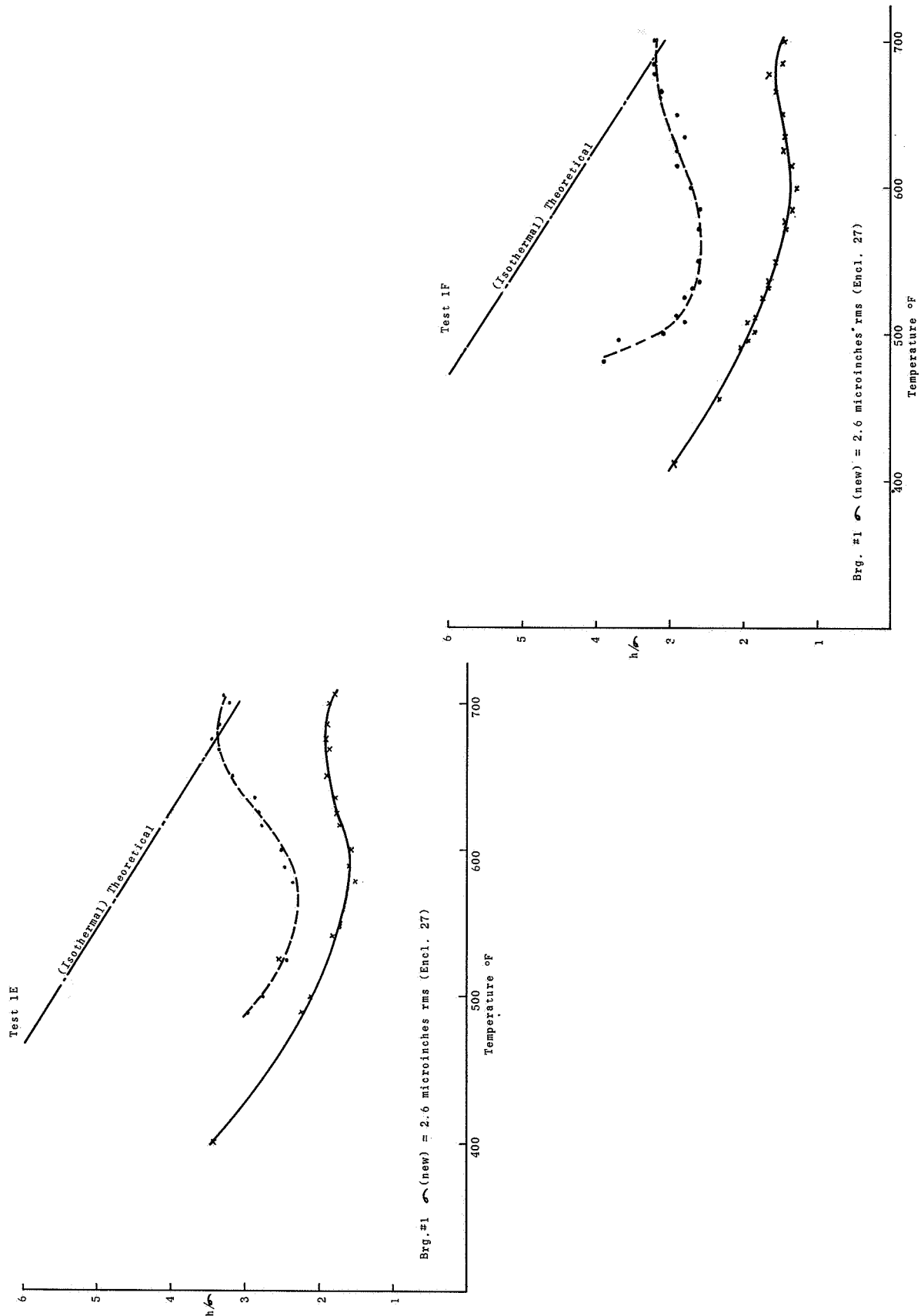
ENCLOSURE 19^B

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 1 SHOWING DATA POINTS
 LUBRICANT-MOBIL XRM-109F, SPEED 43,000 RPM, THRUST LOAD-459 LBS.
 LEGEND: Conductivity --- Capacitance — Too Low to Measure+++++



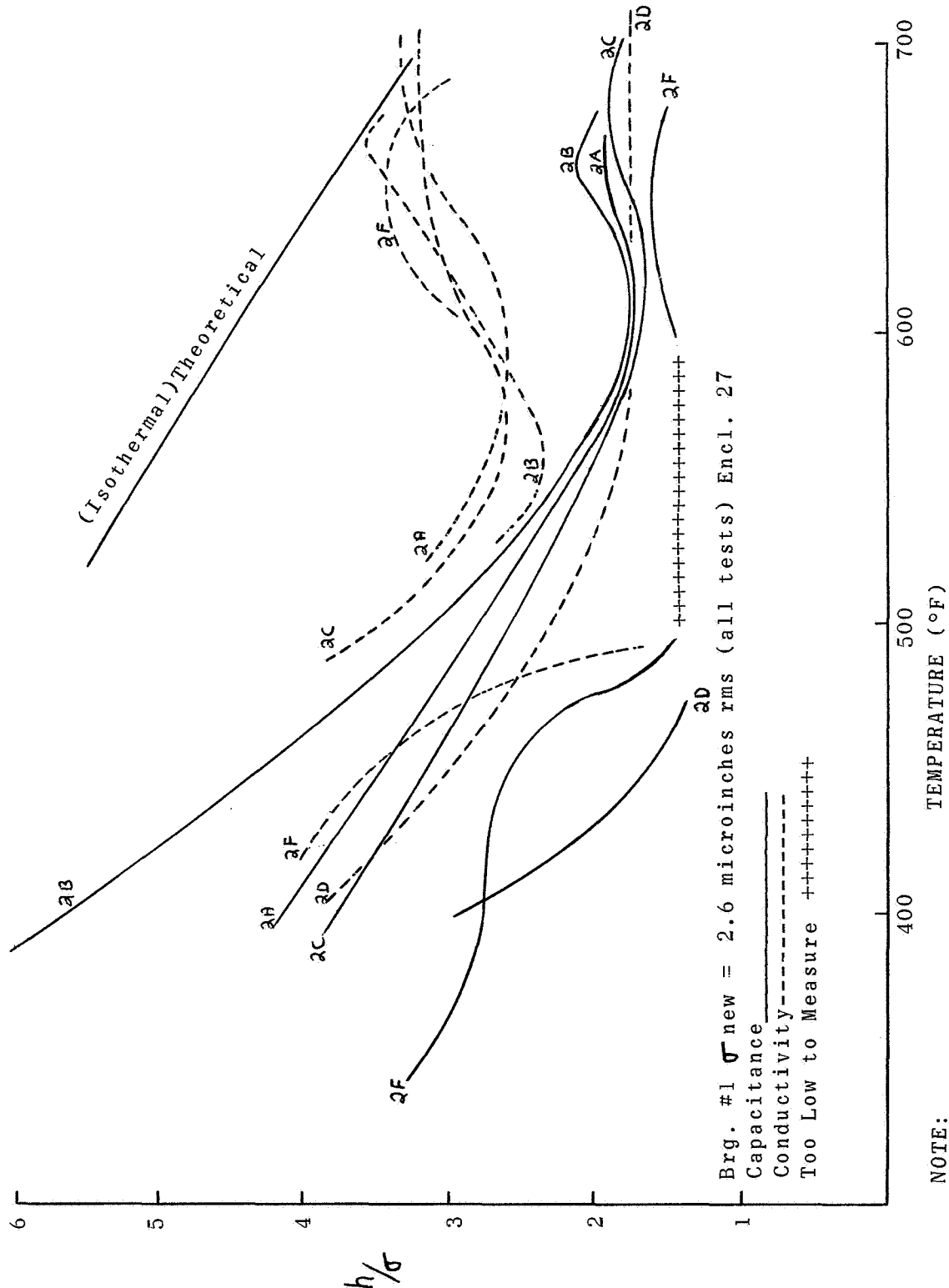
ENCLOSURE 19 B (Cont'd)

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 1 SHOWING DATA POINTS
 LUBRICANT-MOBIL XRM-109F, SPEED-43,000 RPM, THRUST LOAD-459 LBS.
 LEGEND: Conductivity --- Capacitance ——— Too Low to Measure+++++



ENCLOSURE 20A

Composite Plots of Lubricant Film Condition Vs. Bearing Temperature for Test Series No. 2, Lubricant-Mobil XRM-109F,
Speed - 43,000 rpm, Thrust Load - 300 Lbs.

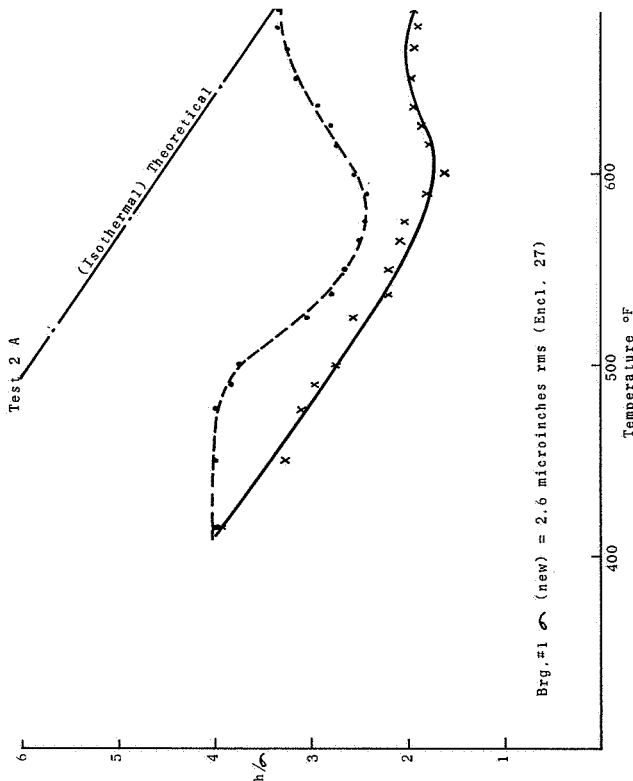
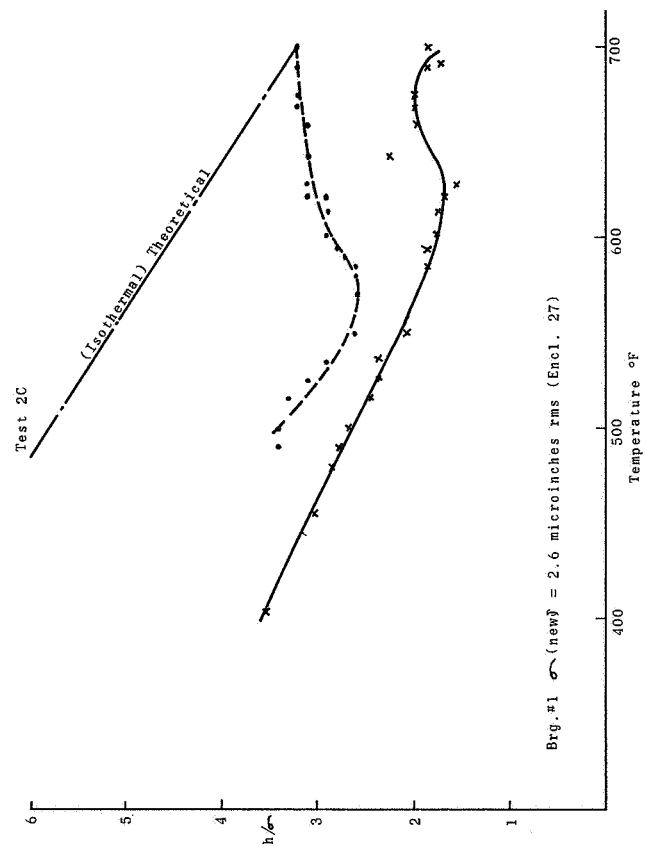
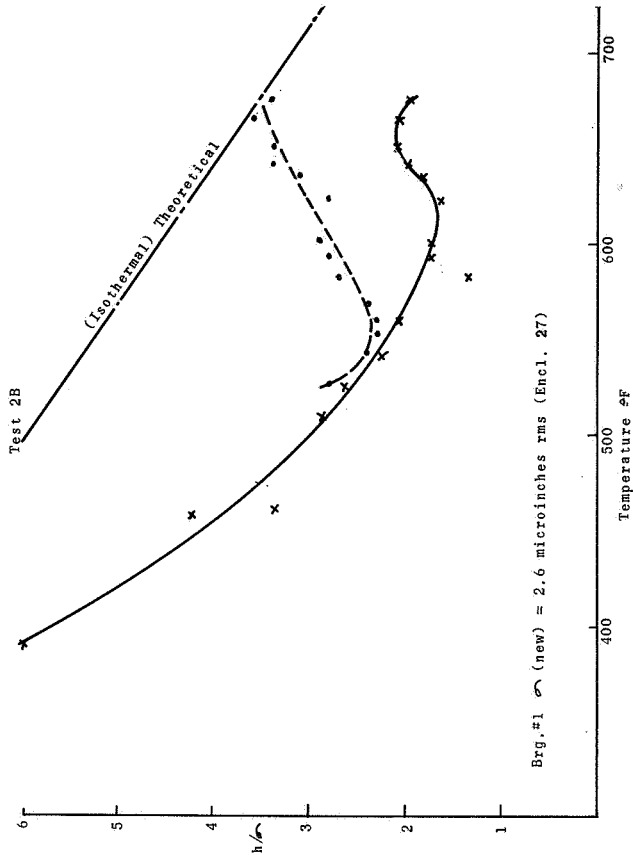


NOTE:

1. The conductivity plot for run 2D was not drawn continuous for purposes of clarity
2. The conductivity plot for run 2F is not continuous

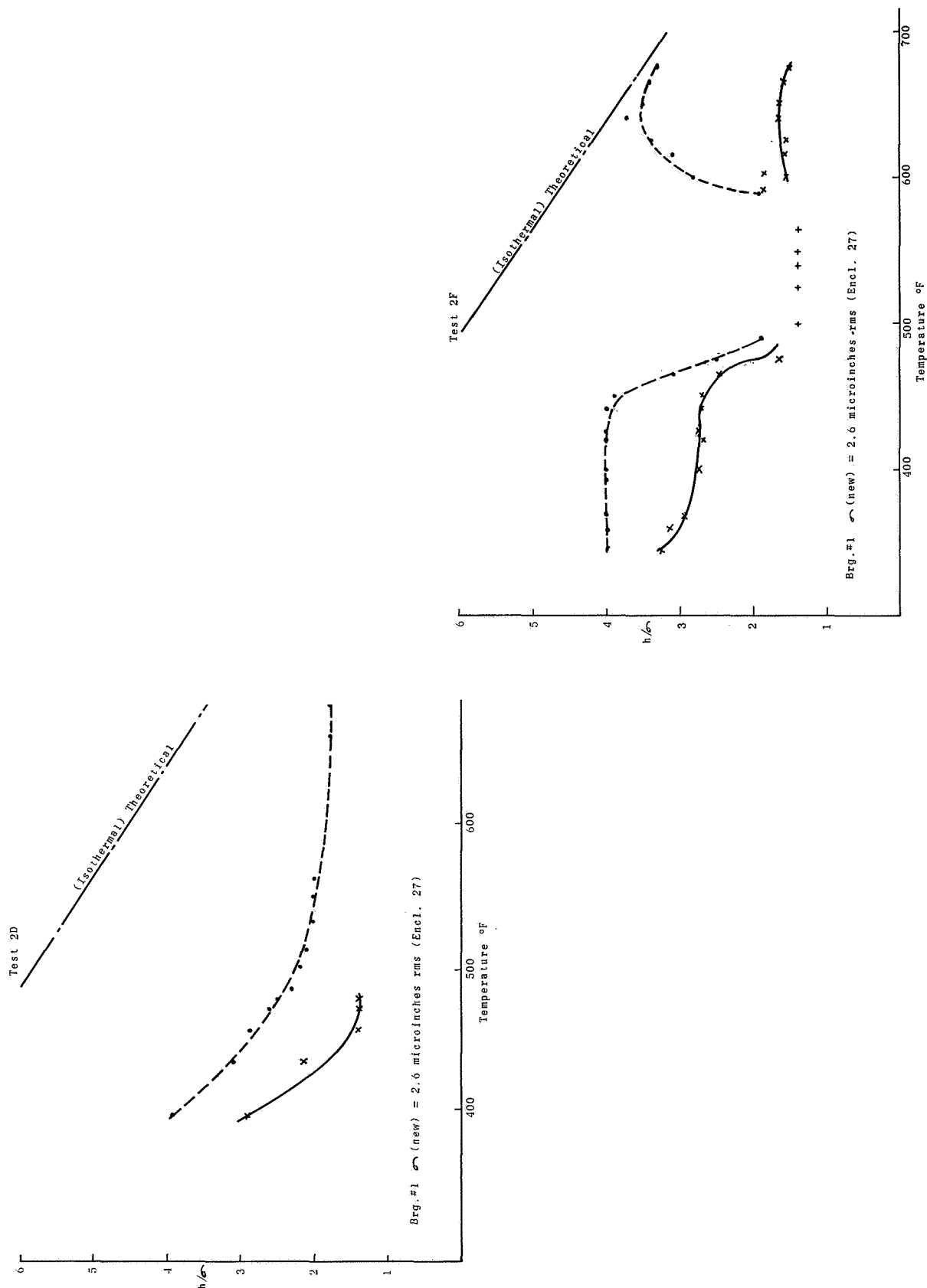
ENCLOSURE 20_B

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 2 SHOWING DATA POINTS
 LUBRICANT-MOBIL XRM-109F, SPEED-43,000 RPM, THRUST LOAD-300 LBS.
 LEGEND: Conductivity--- Capacitance----- Too Low to Measure+++++

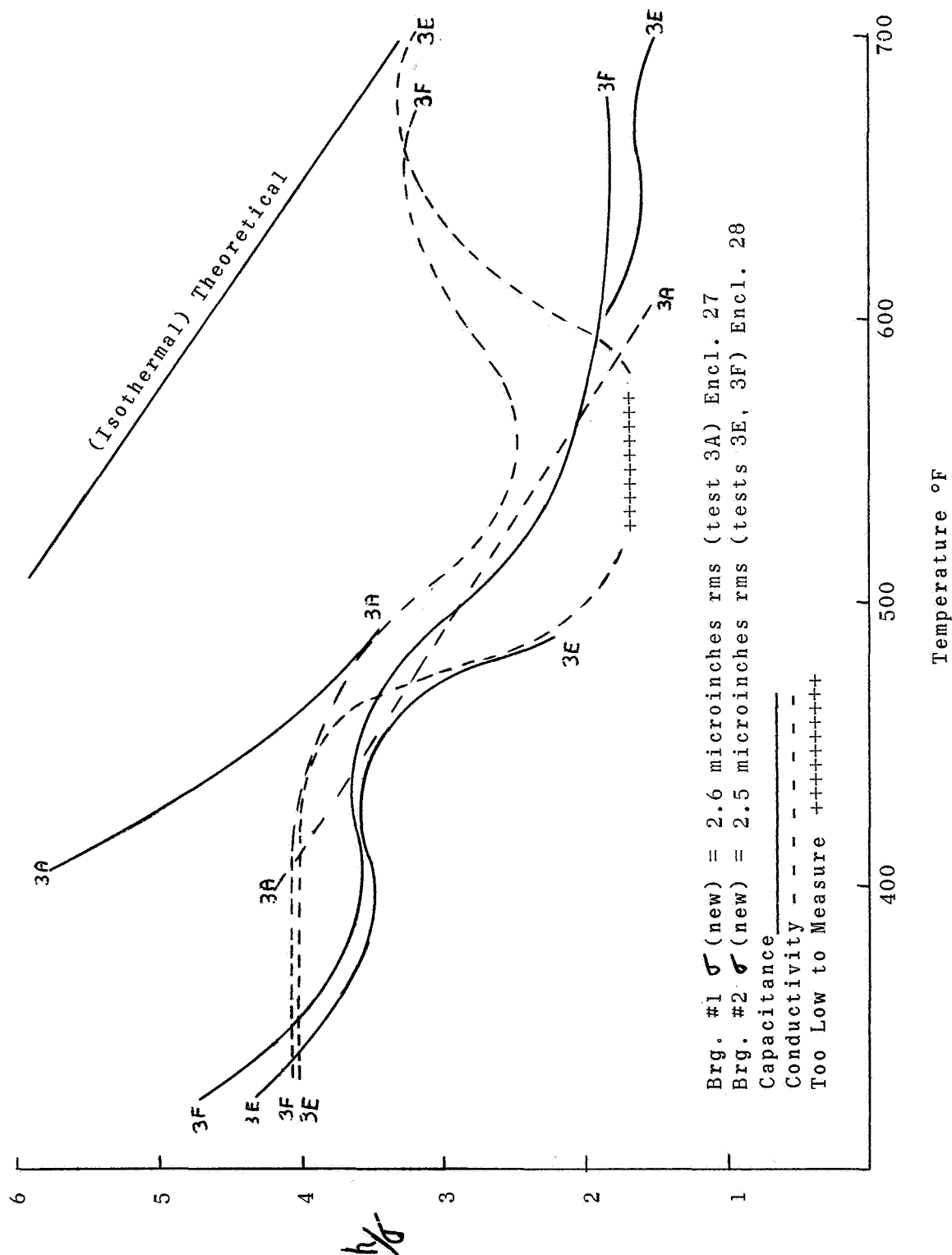


ENCLOSURE 20_B (CONT'D)

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 2 SHOWING DATA POINTS
 LUBRICANT-MOBIL XRM-109F, SPEED-43,000 RPM, THRUST LOAD-300 LBS.
 LEGEND: Conductivity--- Capacitance— Too Low to Measure+++++

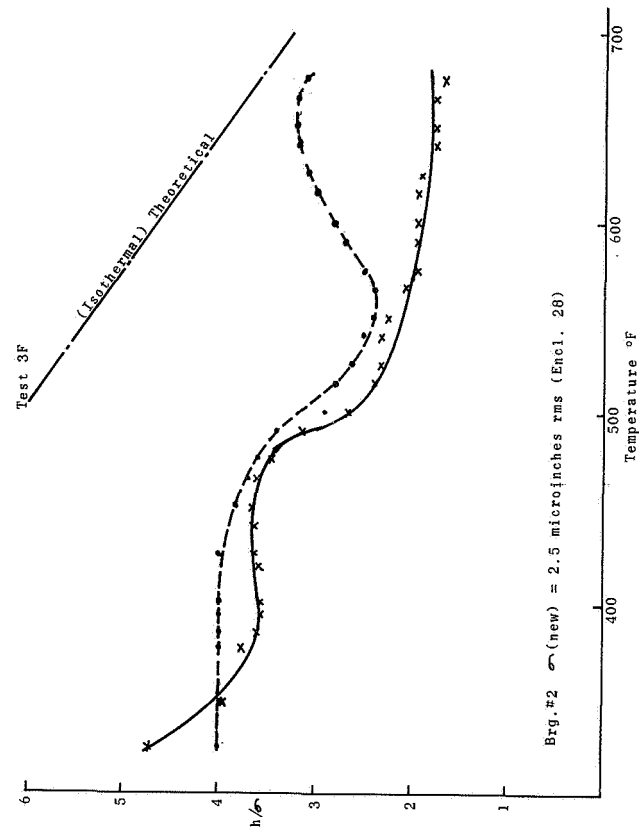
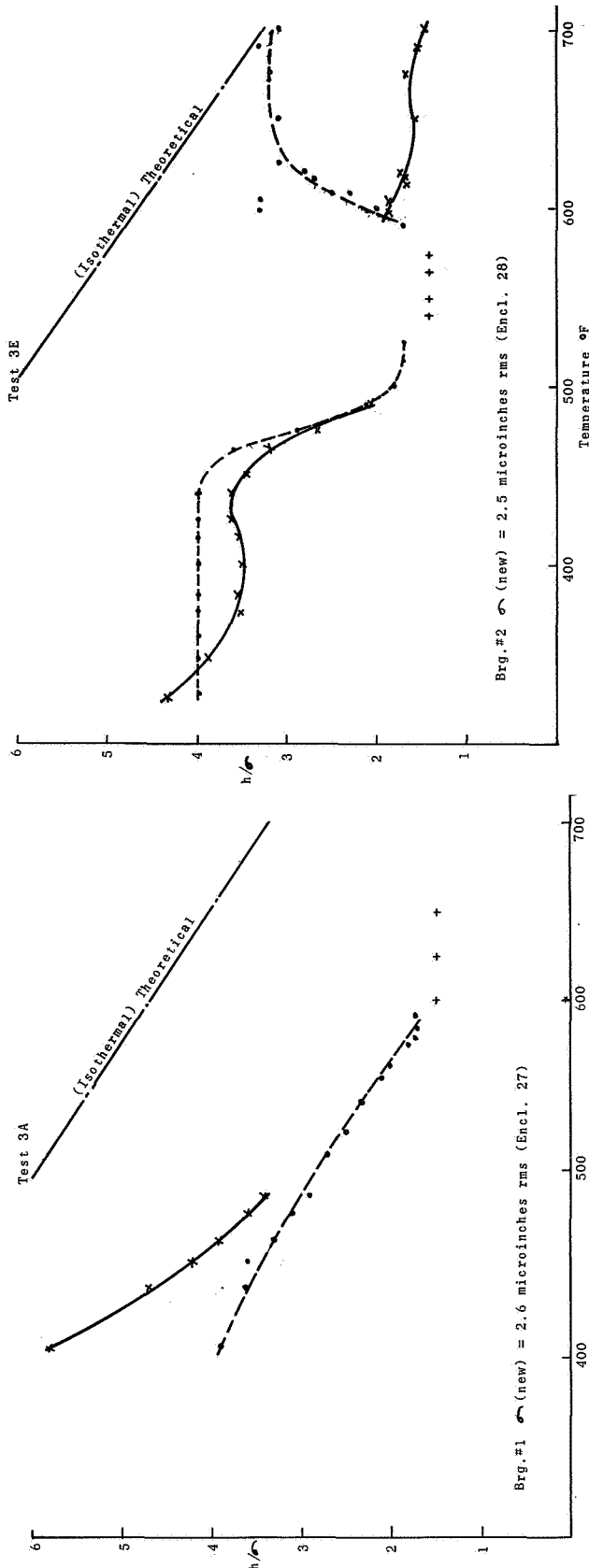


Composite Plots of Lubricant Film Condition Vs. Bearing Temperature for Test Series No. 3, Lubricant-Mobil XRM-109F, Speed - 43,000 rpm, Thrust Load - 200 lbs.



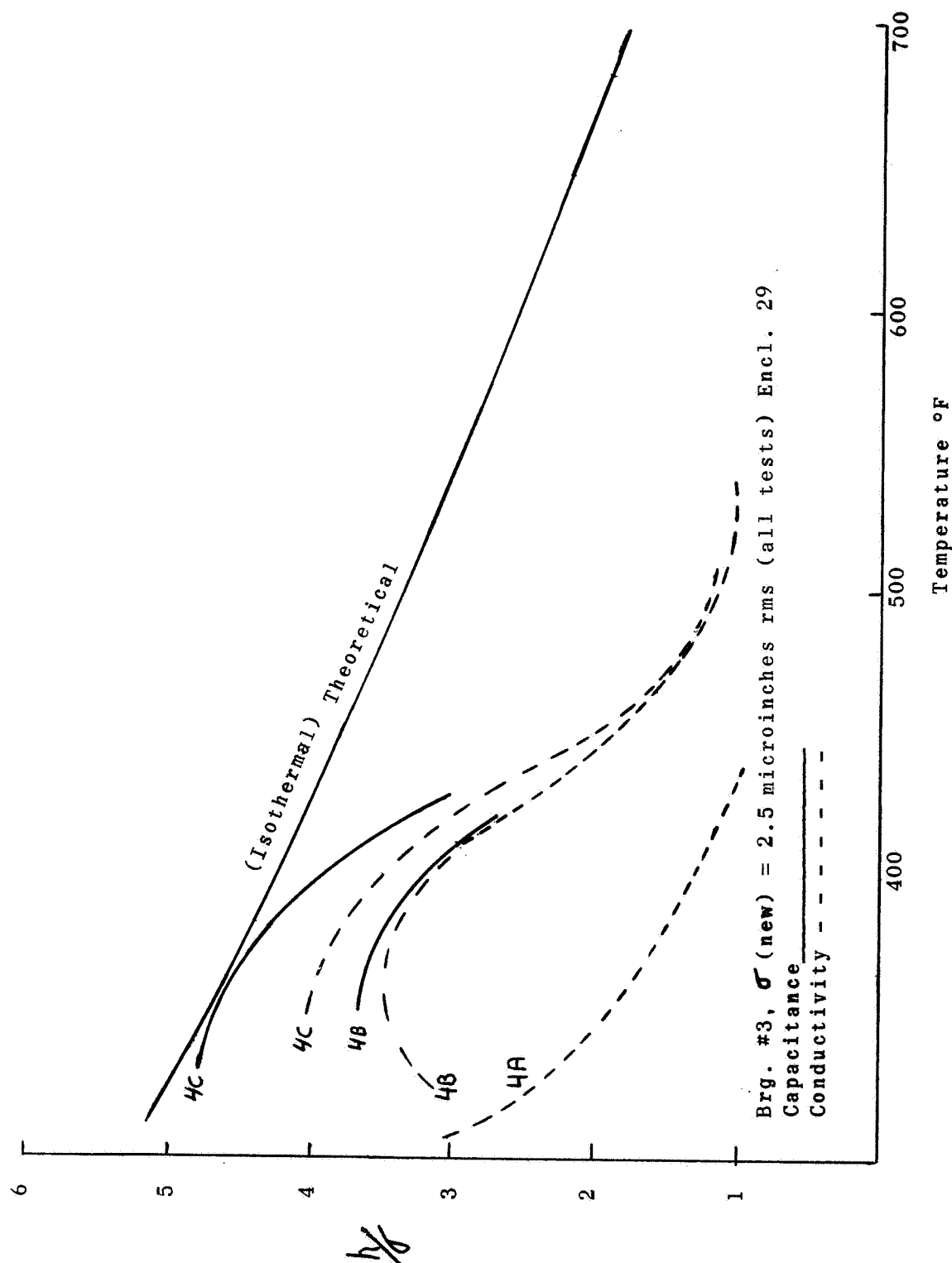
ENCLOSURE 21_B

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 3 SHOWING DATA POINTS
 LUBRICANT-MOBIL XRM-109F, SPEED-43,000 RPM, THRUST LOAD-200 LBS.
 LEGEND: Conductivity --- Capacitance — Too Low to Measure+++++



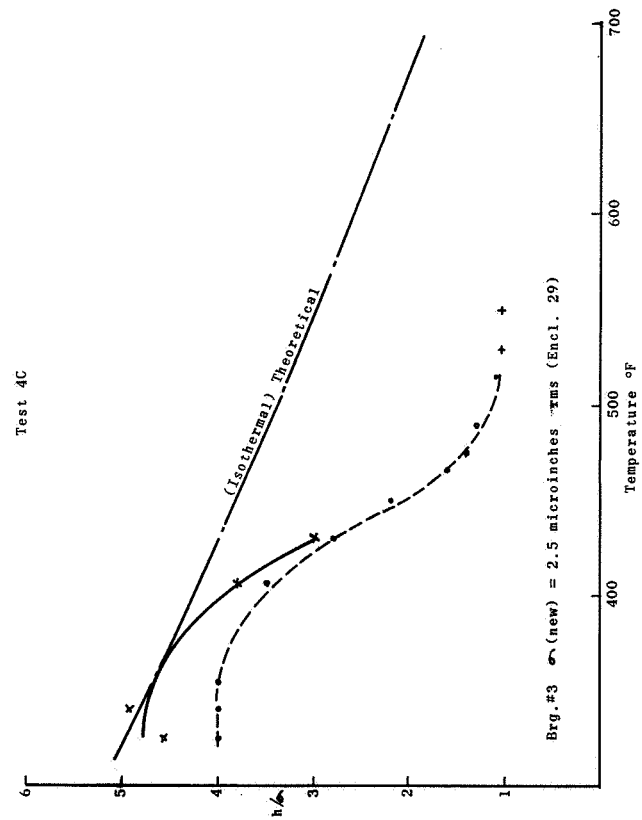
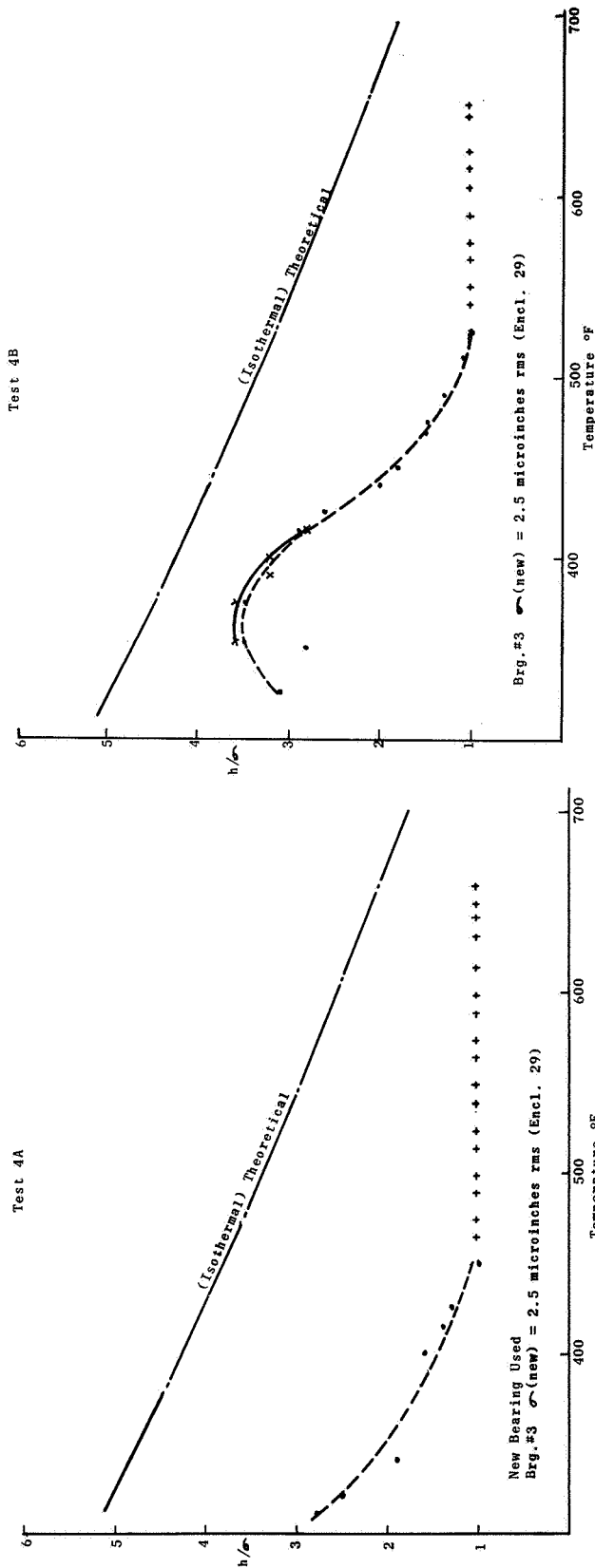
ENCLOSURE 22 A

Composite Plots of Lubricant Film Conditions Vs. Bearing Temperature for Test Series No. 4, Lubricant-Mobil XRM-109F,
Speed - 20,000 rpm, Thrust Load - 345 Lbs.



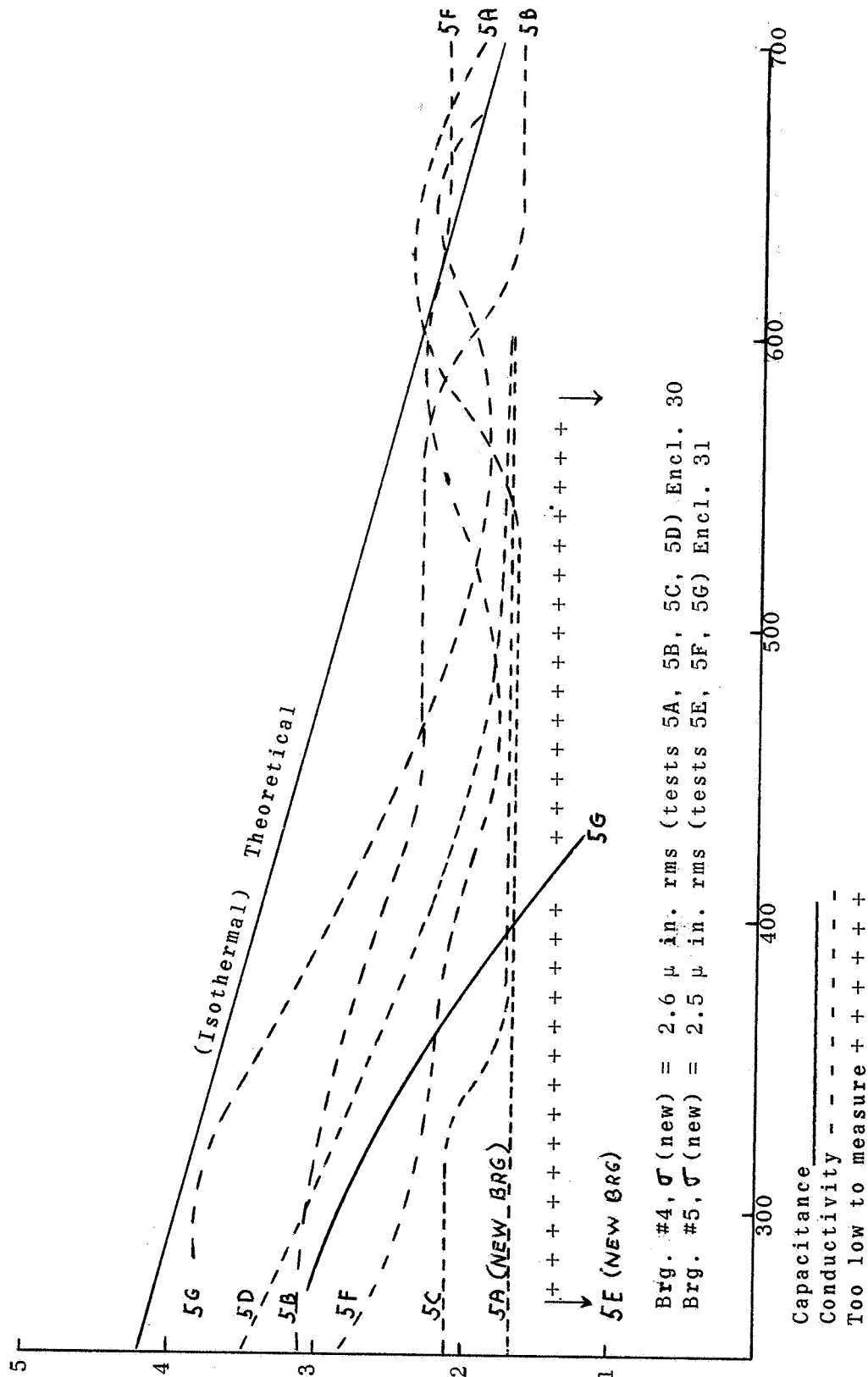
ENCLOSURE 22_B

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 4 SHOWING DATA POINTS
 LUBRICANT-MOBIL XRM-109F, SPEED-20,000 RPM, THRUST LOAD-345 LBS.
 LEGEND: Conductivity:..... Capacitance----- Too Low to Measure+++++



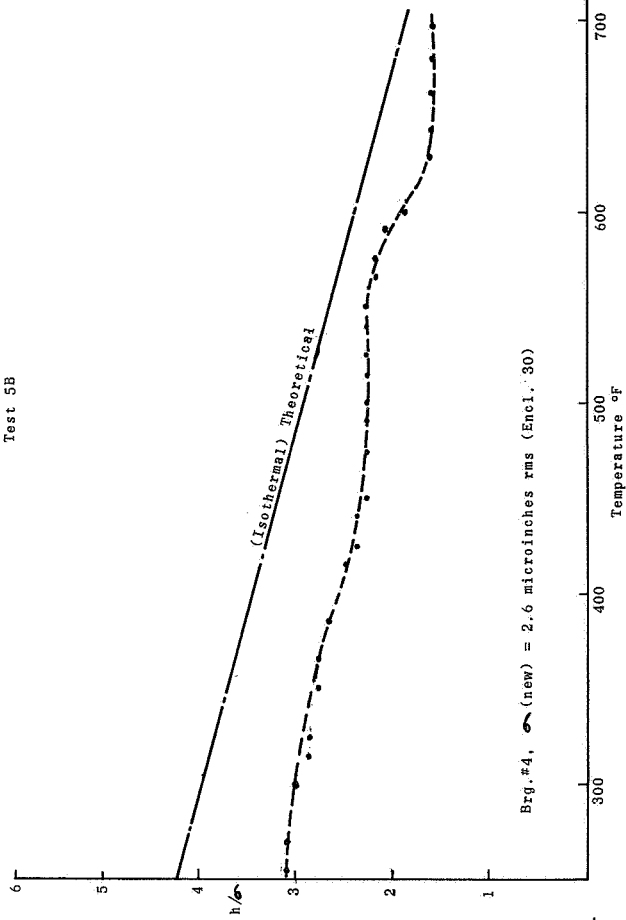
ENCLOSURE 23A

Composite Plots of Lubricant Film Condition Vs. Bearing Temperature for Test Series No. 5, Lubricant-Sinclair Turbo-S Oil 15, Speed - 43,000 rpm, Thrust Load - 300 Lbs.

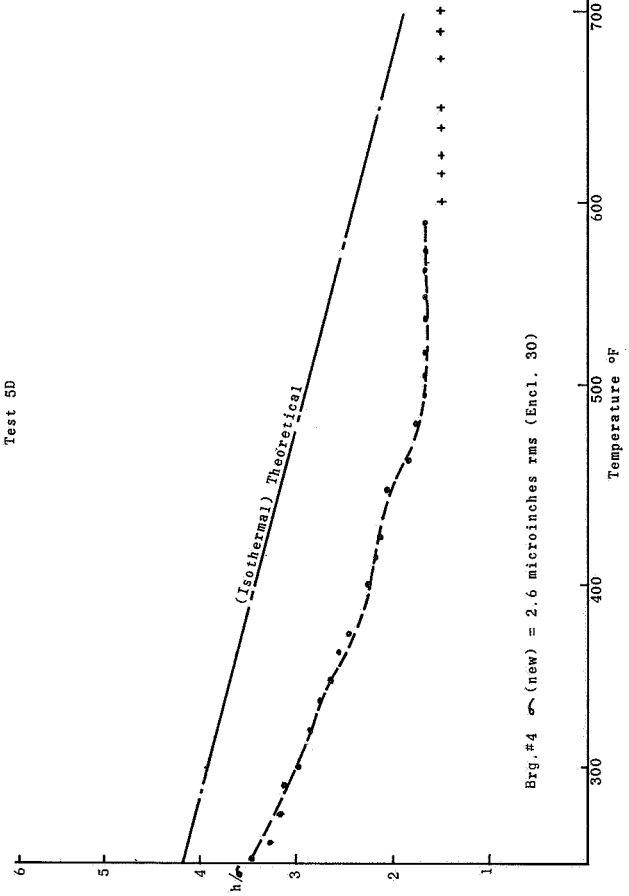


INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 5 SHOWING DATA POINTS
 LUBRICANT-SINCLAIR TURBO-S OIL 15, SPEED-43,000 RPM, THRUST LOAD-300 LBS.
 LEGEND: Conductivity - - - Capacitance - - - Too Low to Measure+++++

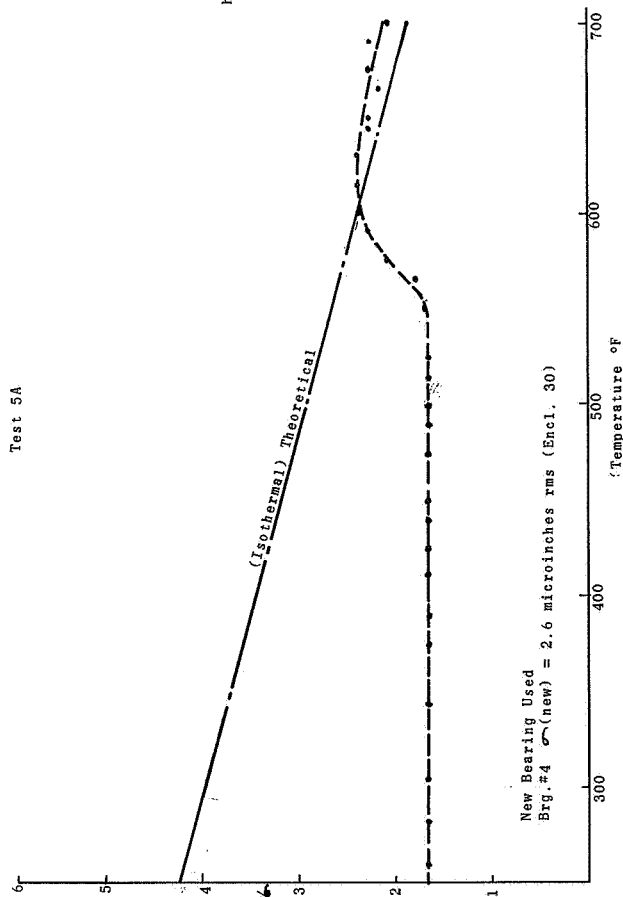
Test 5B



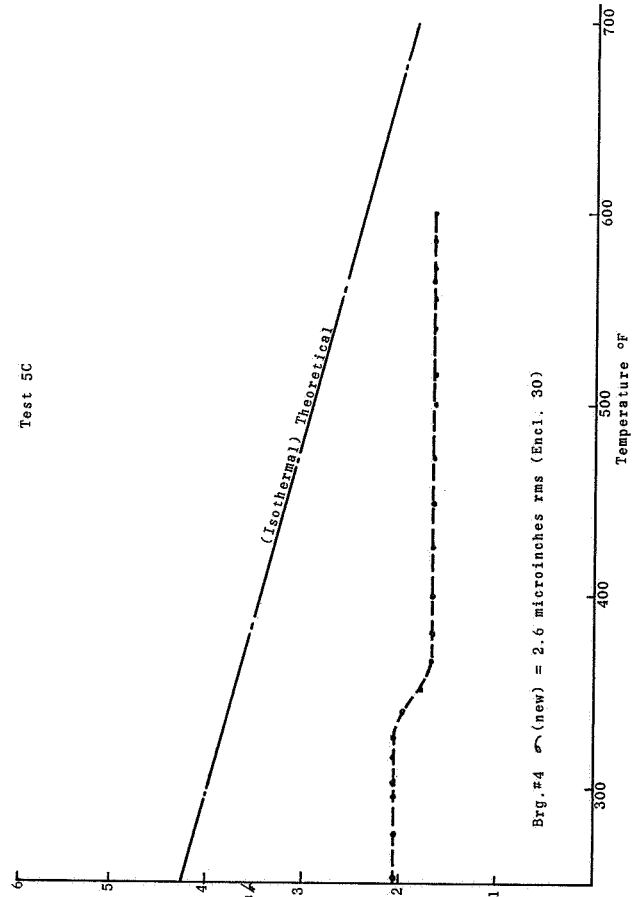
Test 5D



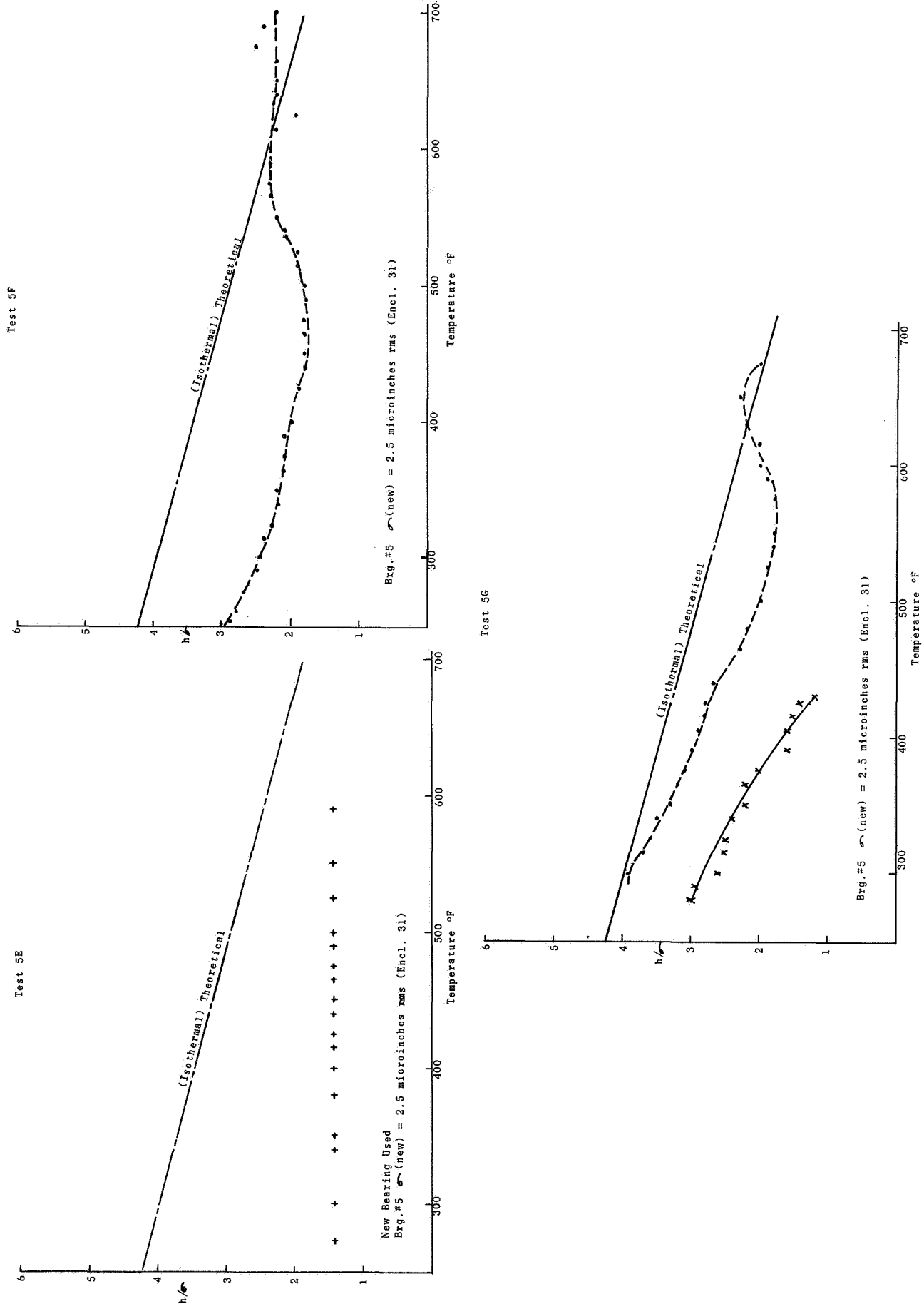
Test 5A



Test 5C

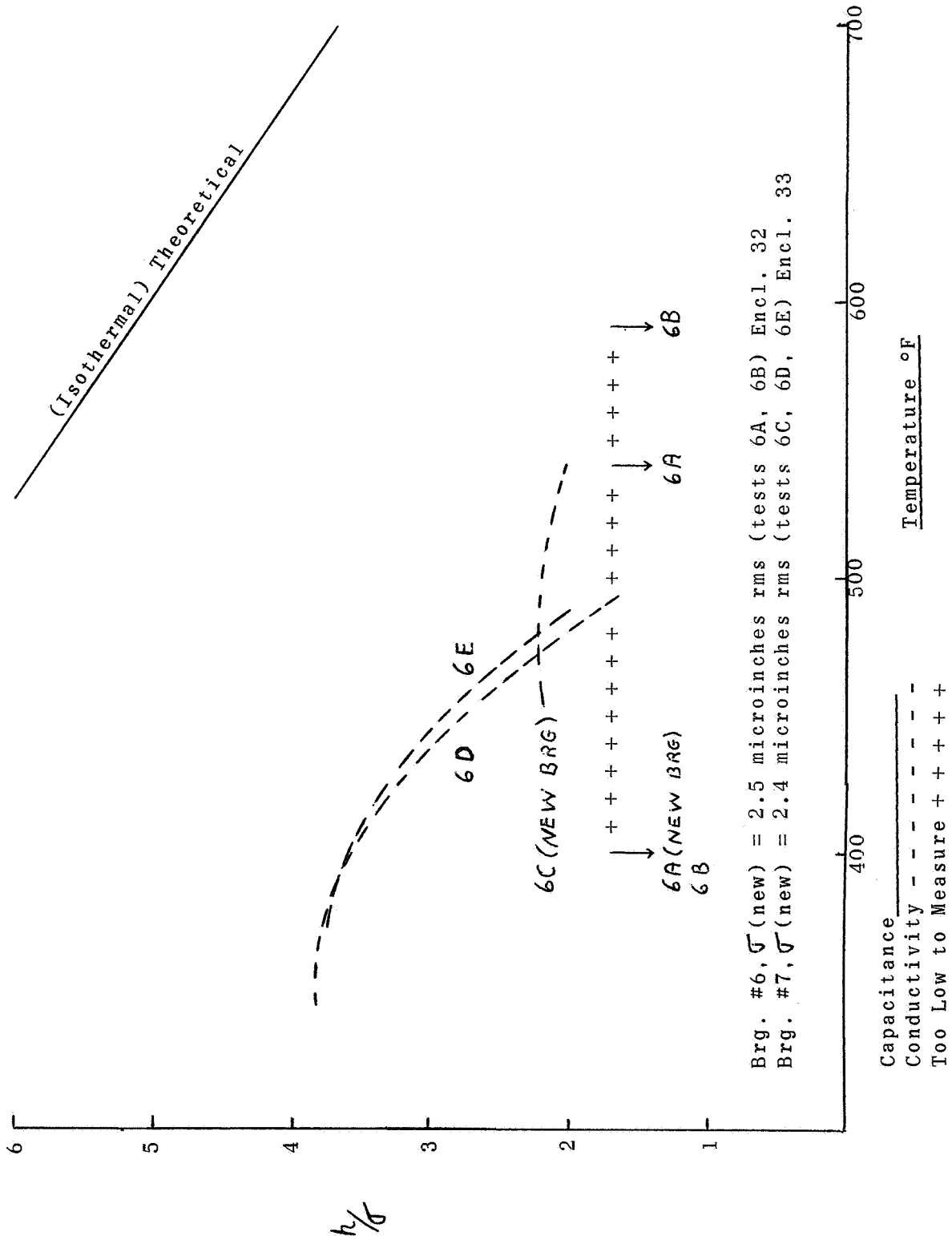


INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 5 SHOWING DATA POINTS
 LUBRICANT-SINCLAIR TURBO-S OIL 15, SPEED-43,000 RPM, THRUST LOAD-300 LBS.
 LEGEND: Conductivity--- Capacitance----- Too Low to Measure+++++



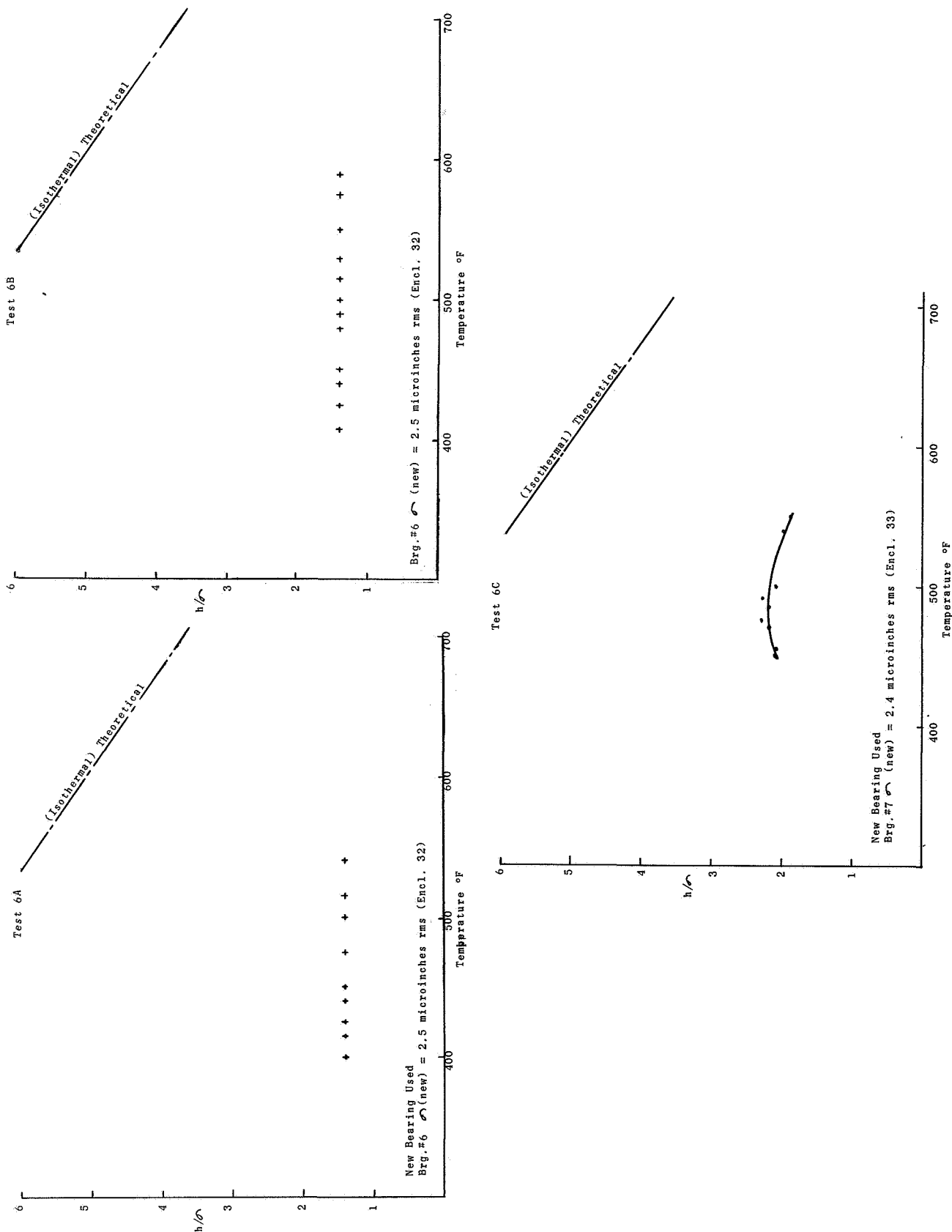
ENCLOSURE 24A

Composite Plots of Lubricant Film Condition Vs. Bearing Temperature for Test Series No. 6, Lubricant - Monsanto MCS-354, Speed - 43,000 rpm, Thrust Load - 300 Lbs.



ENCLOSURE 24^B

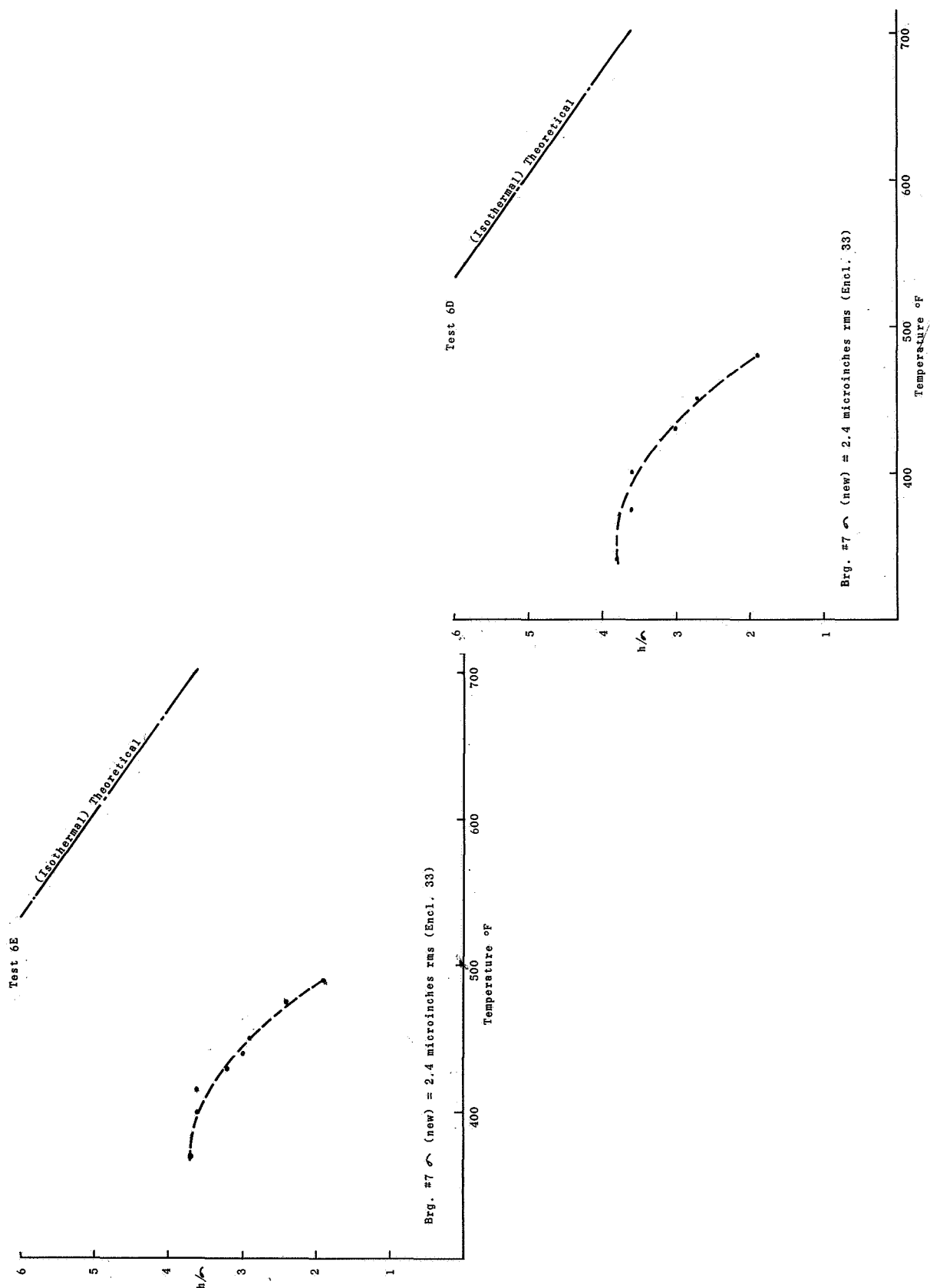
INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 6 SHOWING DATA POINTS
LUBRICANT-MONSANTO MCS-354, SPEED-43,000 RPM, THRUST LOAD-300 LBS.
LEGEND: Conductivity --- Capacitance --- Too Low to Measure+++++



ENCLOSURE 24_B (CONT'D)

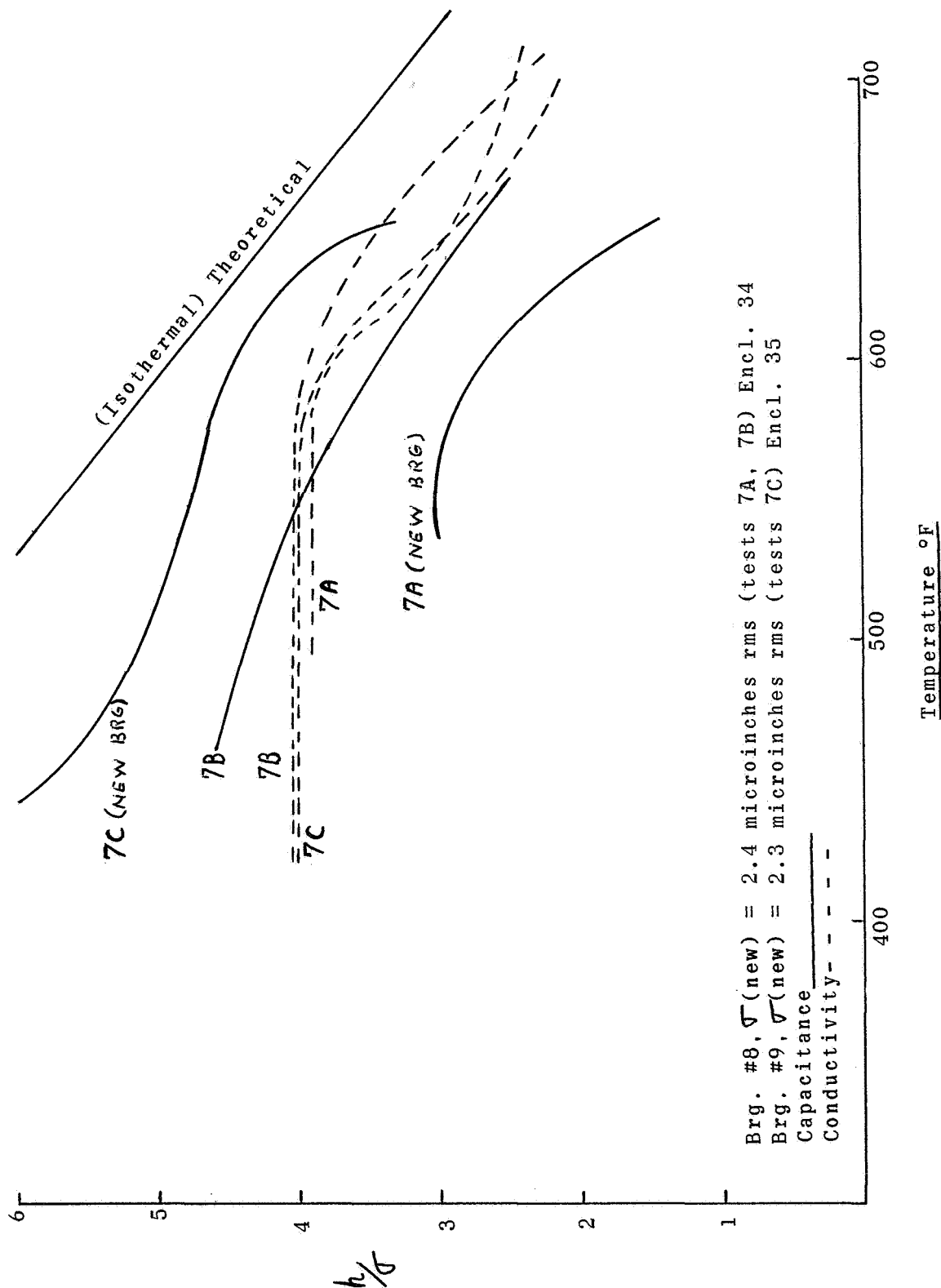
INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 6 SHOWING DATA POINTS
 LUBRICANT-MONSANTO MCS-354, SPEED-43,000 RPM, THRUST LOAD-300 LBS.

LEGEND: Conductivity --- Capacitance ——— Too Low to Measure+++++



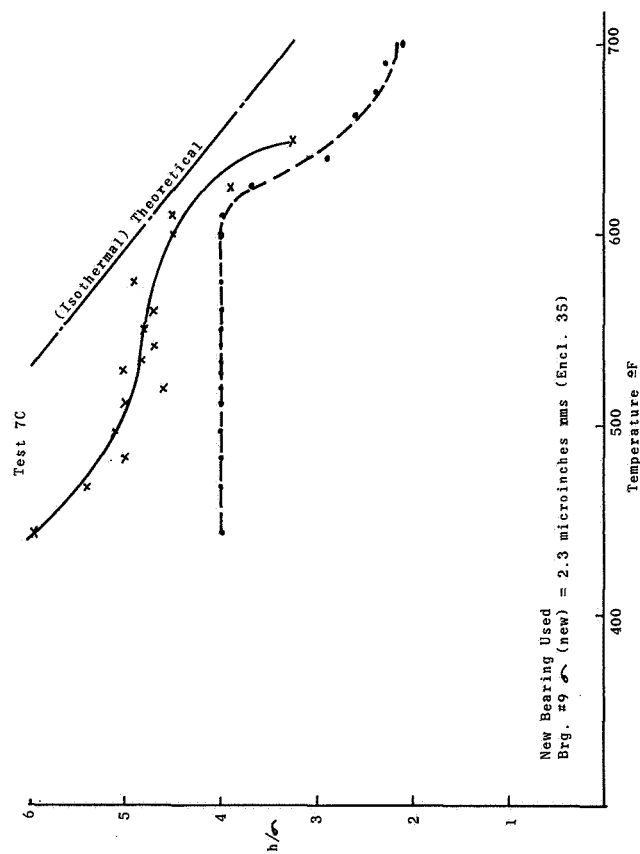
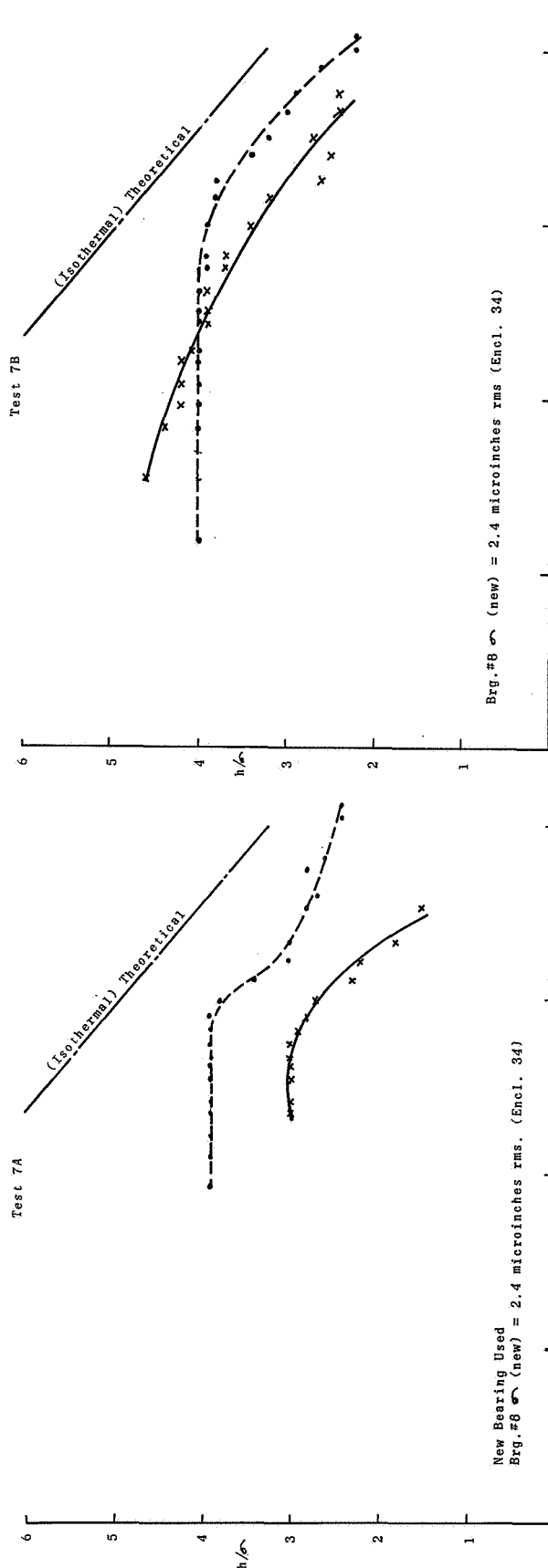
ENCLOSURE 25A

Composite Plots of Lubricant Film Condition Vs. Bearing Temperature for Test Series No. 7, Lubricant - DuPont Krytox 143AC, Speed - 43,000 rpm, Thrust Load - 300 Lbs.



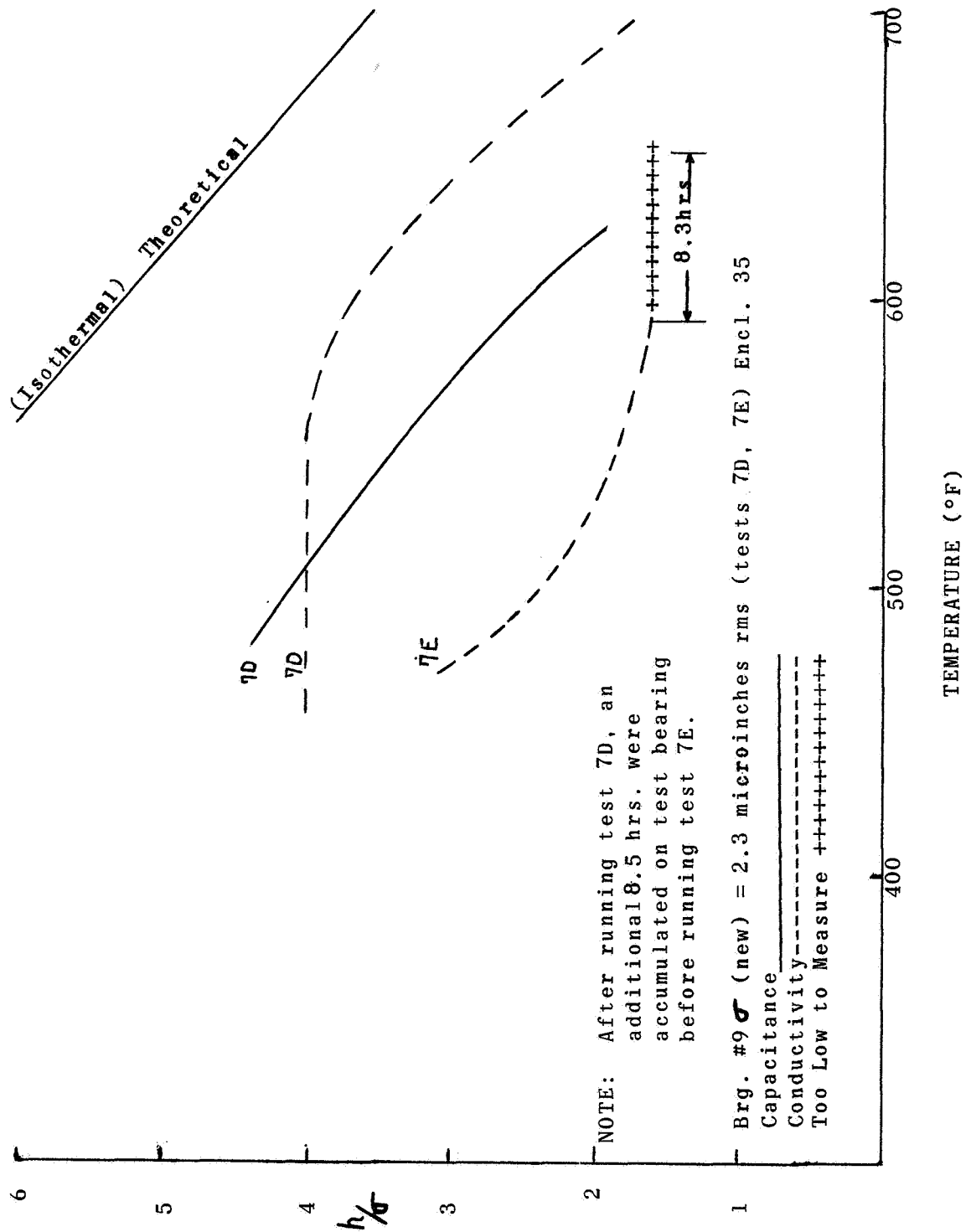
ENCLOSURE 25_B

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 7 SHOWING DATA POINTS
 LUBRICANT-DuPONT KRYTOX 143AC, SPEED-43,000 RPM, THRUST LOAD-300 LBS.
 LEGEND: Conductivity--- Capacitance--- Too Low to Measure+++++



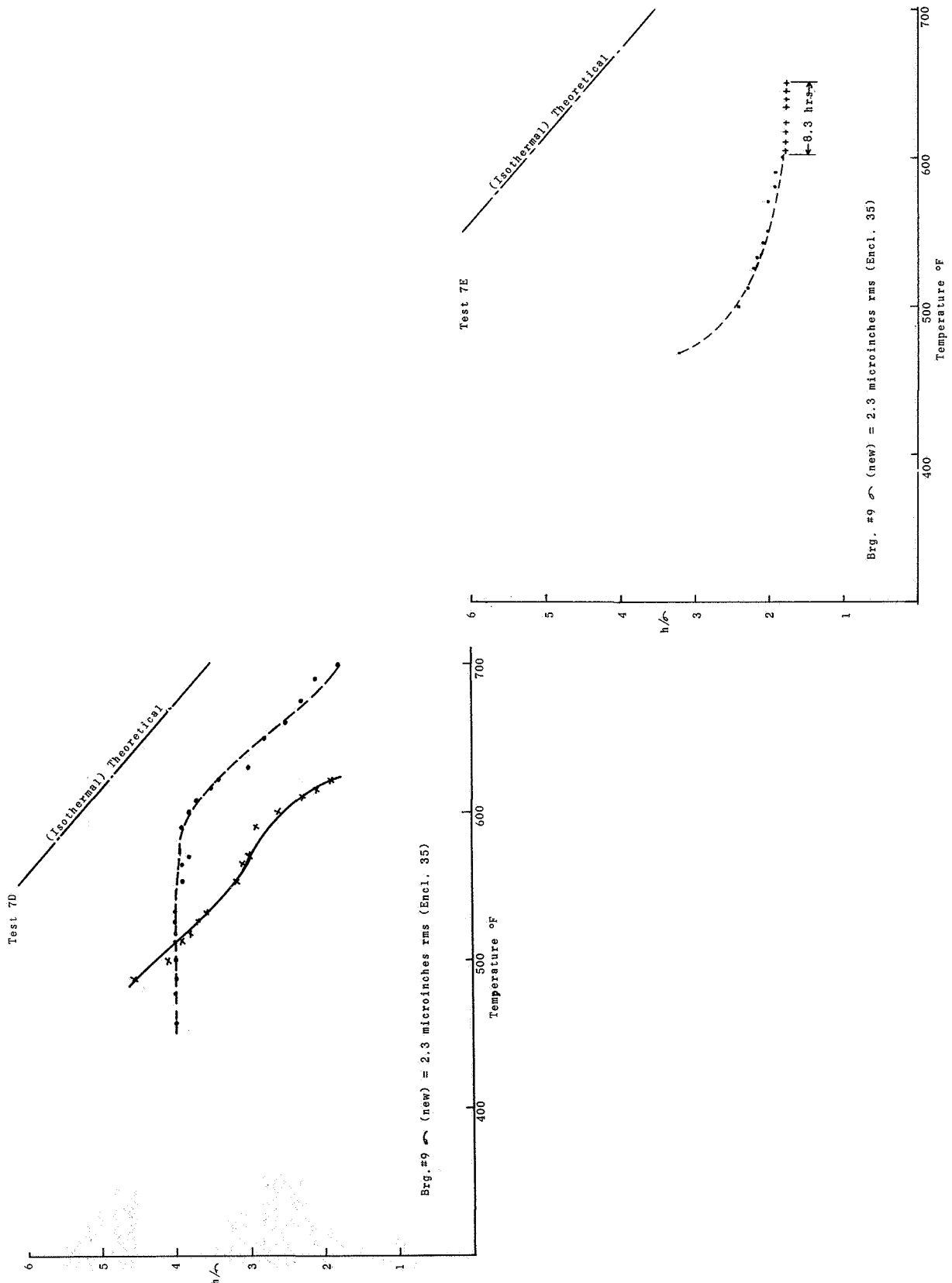
ENCLOSURE 26 A

Composite Plots of Lubricant Film Condition Vs. Bearing Temperature for Test Series No. 7, Lubricant - DuPont Krytox 143AC, Speed - 43,000 rpm, Thrust Load - 459 Lbs.



ENCLOSURE 26^B

INDIVIDUAL PLOTS OF LUBRICANT FILM CONDITION VS. BEARING TEMPERATURE FOR TEST SERIES NO. 7 SHOWING DATA POINTS
 LUBRICANT-DUPONT KRYTOX 143AC, SPEED-43,000 RPM, THRUST LOAD-459 LBS.
 LEGEND: Conductivity--- Capacitance— Too Low to Measure+++++



7205 VAP Test Bearing #1 (327701)

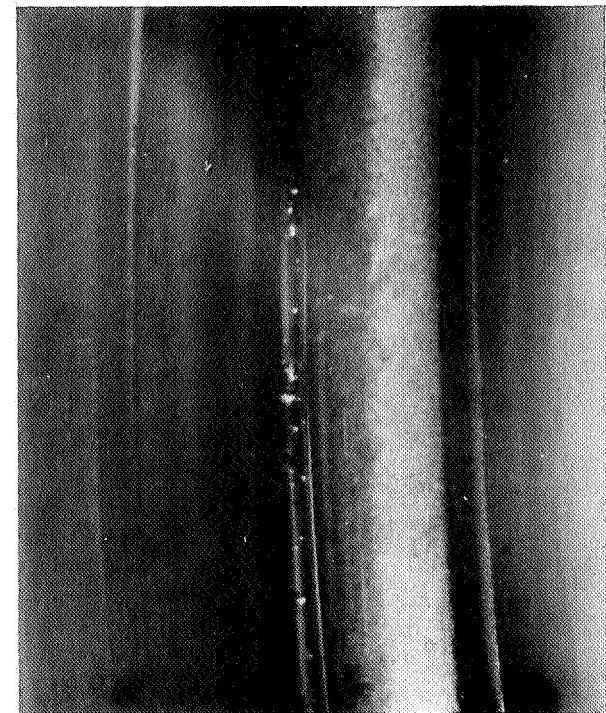
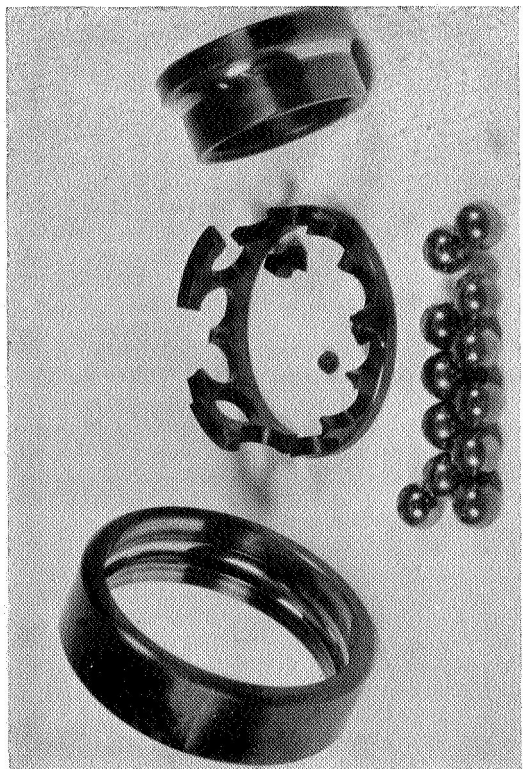
Lubricant Mobil XRM - 109F
Speed 43,000 rpm
Total Hours 41.2

- a. 2.3 hrs. @ 200 lbs.
- b. 16.8 hrs. @ 300 lbs.
- c. 22.1 hrs. @ 459 lbs.

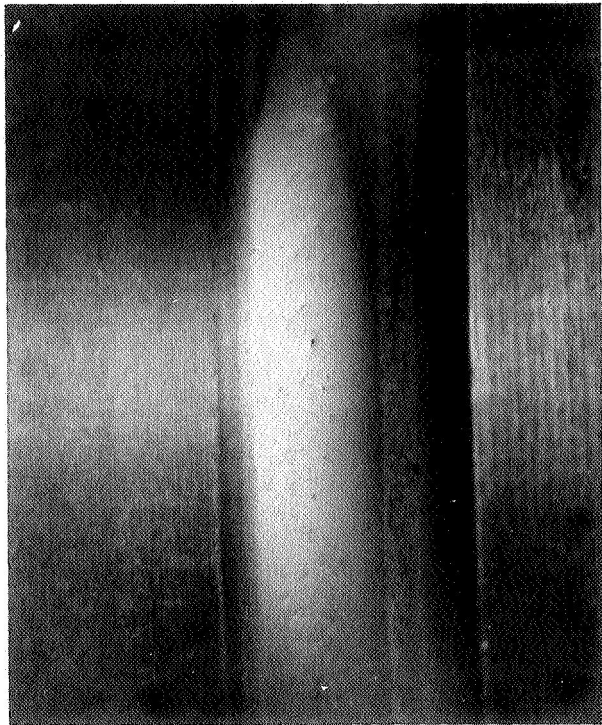
Test Runs 1B, 1C, 1D, 1E, 1F,
2A, 2B, 2C, 2D, 3A

Surface Finish (microinches A.A.)

	Inner	Outer	Balls
New	1.5	1.9	1.6
Tested	2.6	1.7	2.0



Outer Ring



Inner Ring

ENCLOSURE 28

7205 VAP Test Bearing #2 (327702)

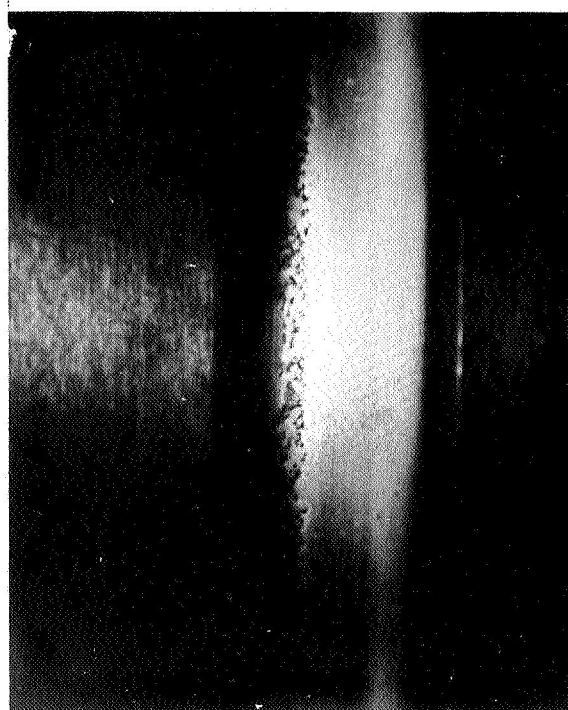
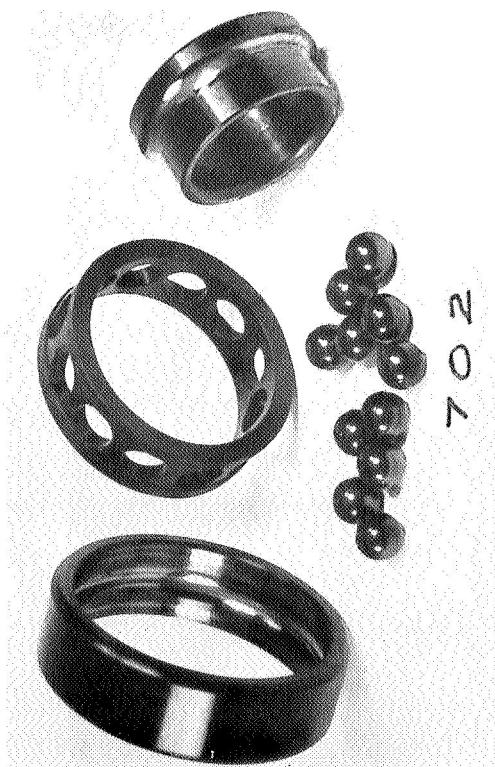
Lubricant Mobil XRM-109F
 Speed 43,000 rpm
 Total Hours 33.3

- a. 9.9 hrs @ 200 lbs.
- b. 21.5 hrs @ 300 lbs.
- c. 1.9 hrs @ 459 lbs.

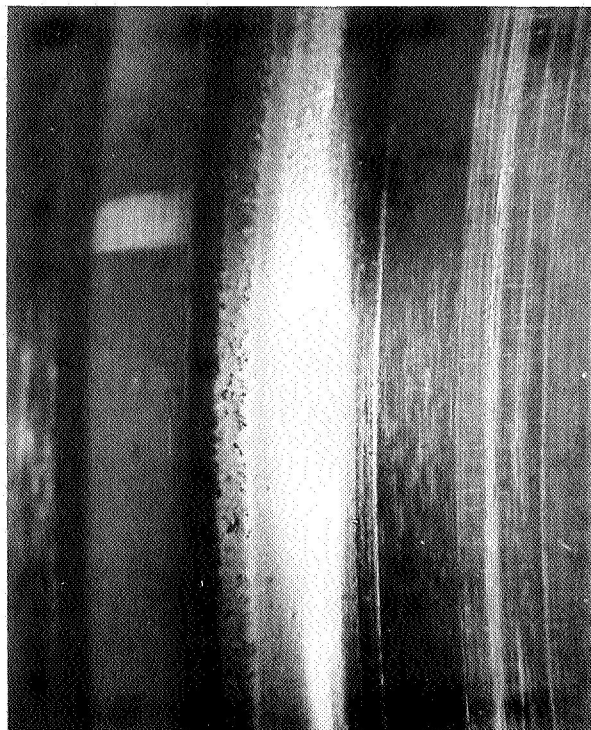
Test Runs 2F, 3E, 3F

Surface Finish (microinches A.A.)

	Inner	Outer	Balls
New	1.5	1.9	1.6
Tested	2.2	1.0	1.7



Inner Ring



Outer Ring

ENCLOSURE 29

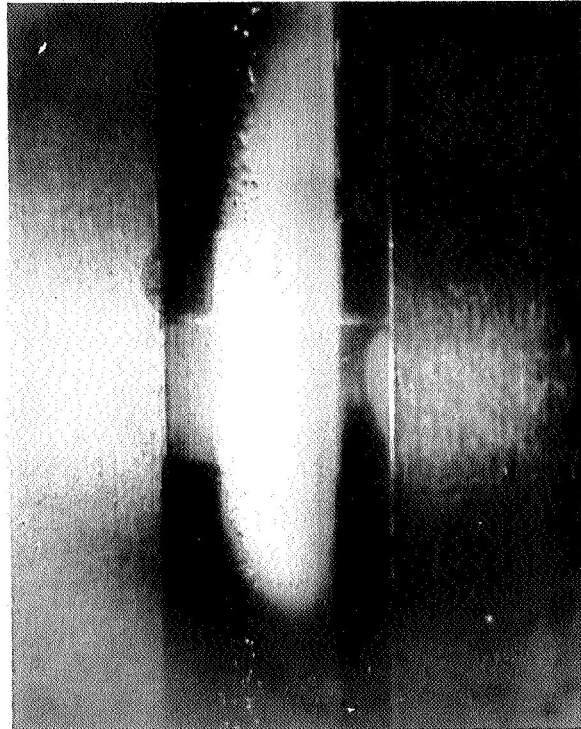
7205 VAP Test Bearing #3 (327703)

Lubricant Mobil XRM-109F
 Speed 20,000 rpm
 Total Hours 7.6 @ 345 lbs.

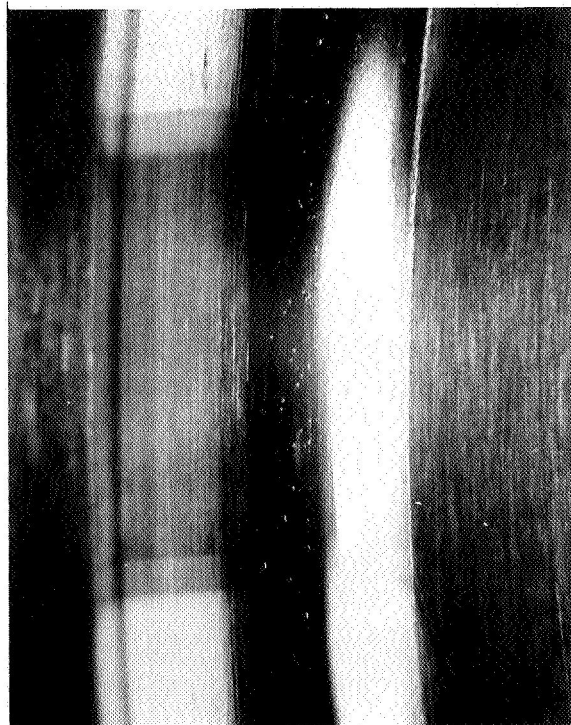
Test Runs 4A, 4B, 4C

Surface Finish (microinches A.A.)

	Inner	Outer	Balls
New	1.4	1.8	1.6
Tested	1.2	1.4	1.7



Inner Ring



Outer Ring

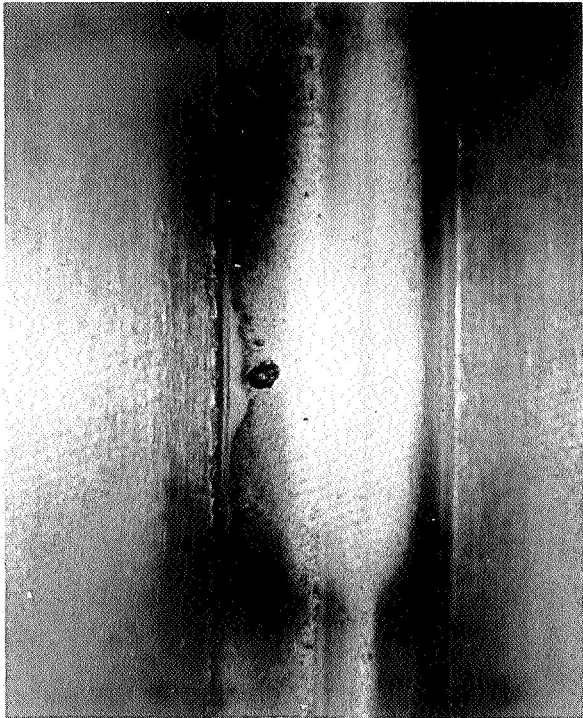
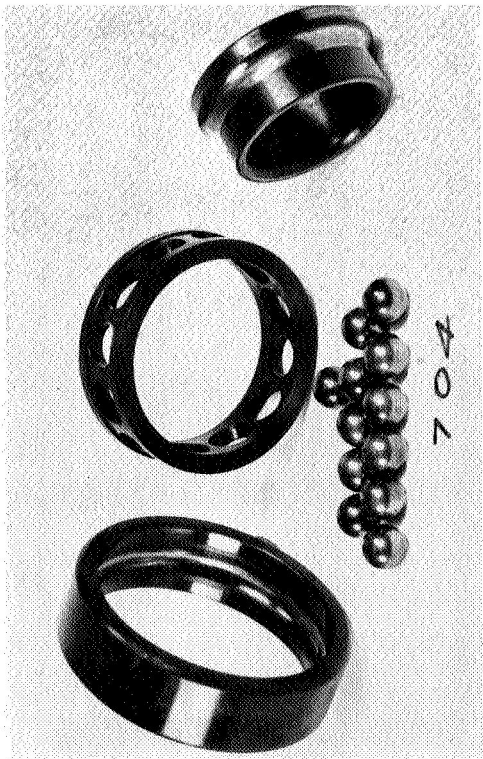
7205 VAP Test Bearing #4 (327704)

Lubricant Sinclair Turbo S Oil 15
Speed 43,000 rpm
Total Hours 7.6 @ 300 lbs.

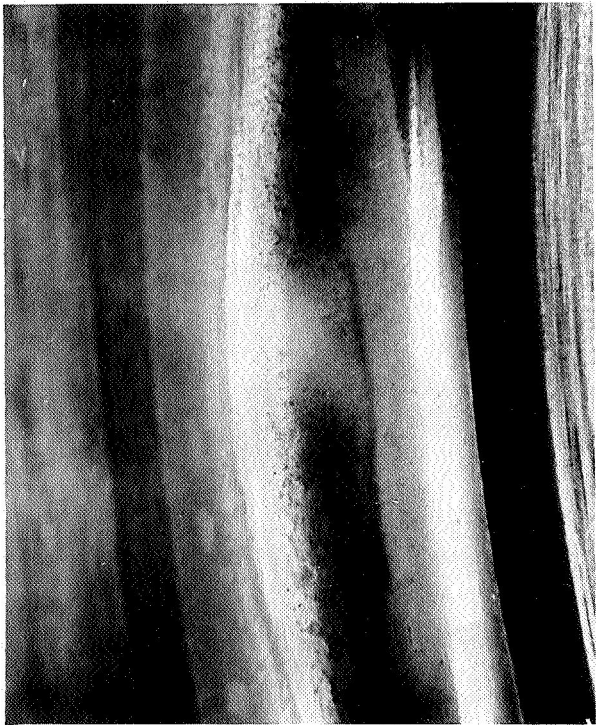
Test Runs 5A, 5B, 5C, 5D

Surface Finish (microinches rms.)

	Inner	Outer	Balls
New	1.4	1.9	1.6
Tested	1.4	-	4.0



Inner Ring



Outer Ring

ENCLOSURE 31

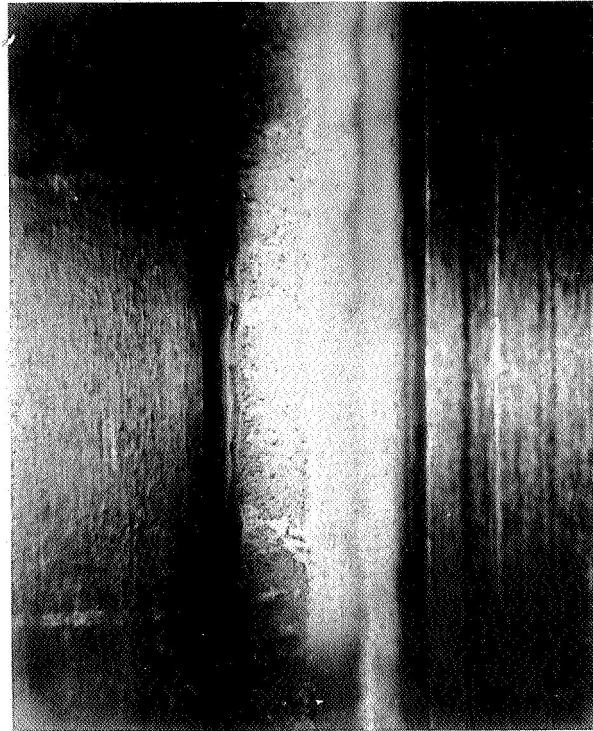
7205 VAP Test Bearing #5 (327705)

Lubricant Sinclair Turbo S Oil 15
 Speed 43,000 rpm
 Total Hours 5.0 @ 300 lbs.

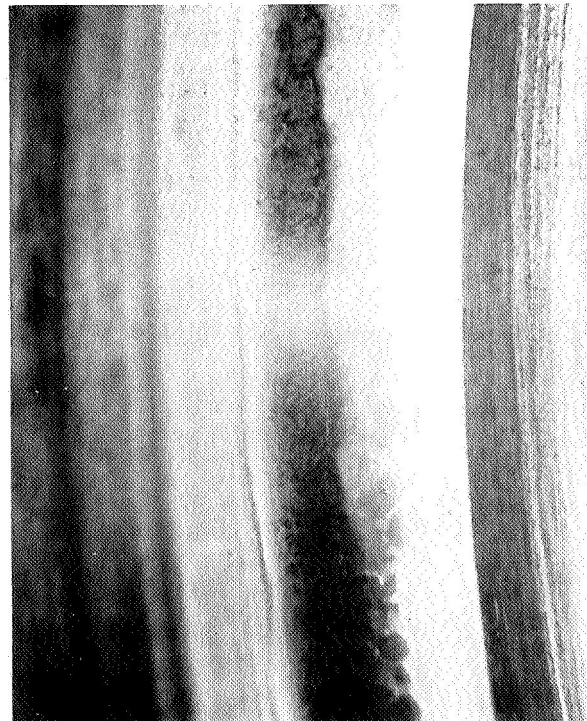
Test Runs 5E, 5F, 5G

Surface Finish (microinches A.A.)

	Inner	Outer	Balls
New	1.4	1.8	1.6
Tested	-	-	7.5



Inner Ring



Outer Ring

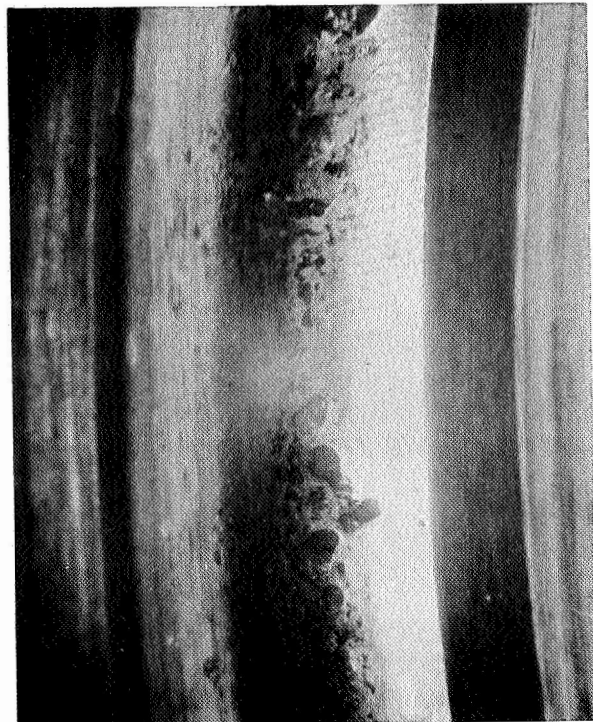
ENCLOSURE 32

7205 VAP Test Bearing #6 (327706)

Lubricant	Monsanto MCS-354
Speed	43,000 rpm
Total Hours	1.75 @ 300 lbs.
Test Runs	6A, 6B
Surface Finish (microinches A.A.)	
Inner	1.4
Outer	1.7
Balls	1.6
New	-
Tested	-



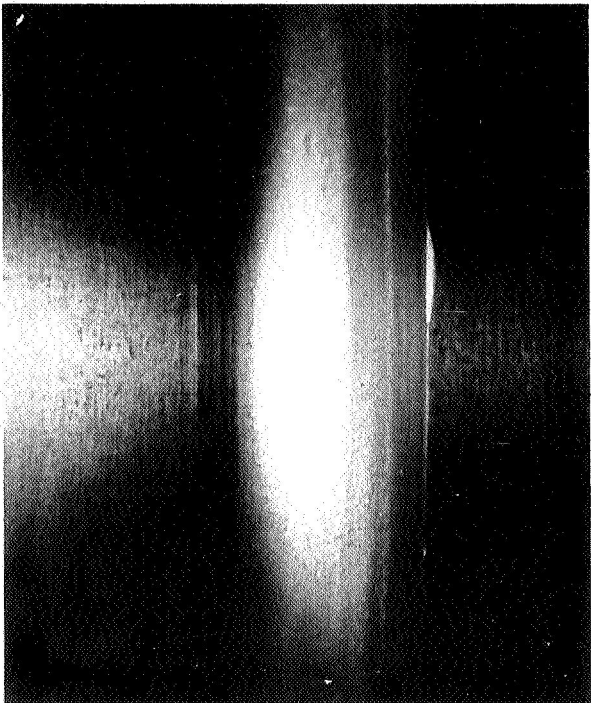
Inner Ring



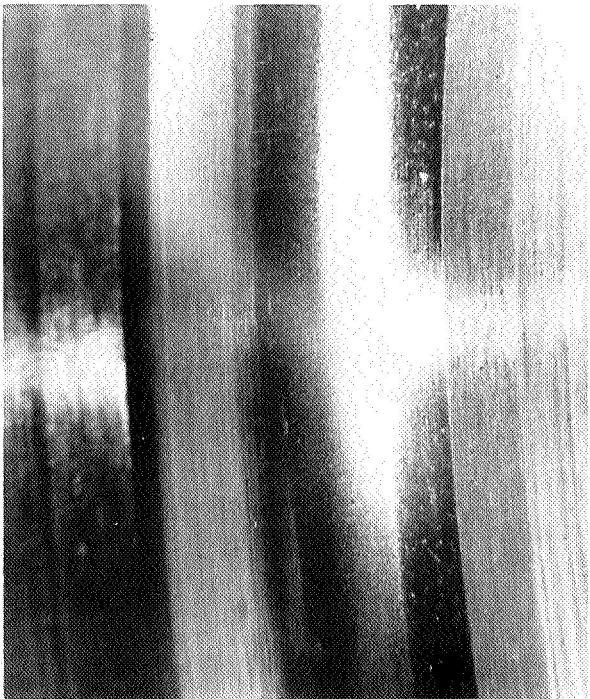
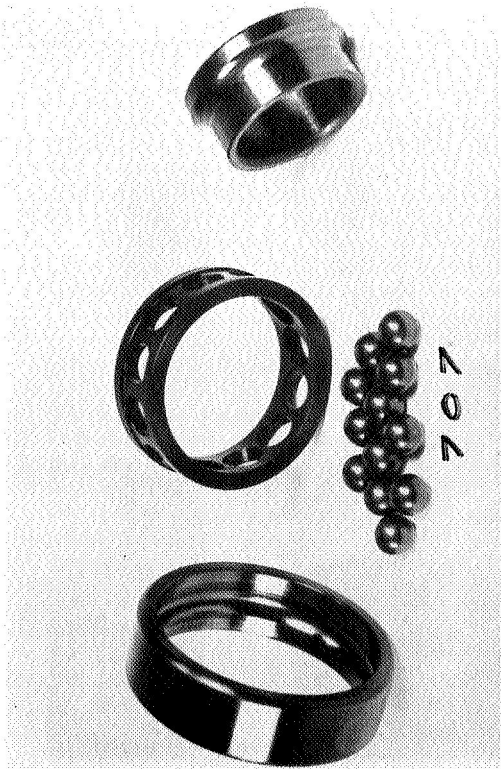
Outer Ring

7205 VAP Test Bearing #7 (327707)

Lubricant Monsanto MCS-354
Speed 43,000 rpm
Total Hours 2.85 @ 300 lbs.
Test Runs 6C, 6D, 6E
Surface Finish (microinches A.A.)
 Inner Outer Balls
New 1.5 1.6 1.6
Tested 1.4 1.6 1.9



Inner Ring

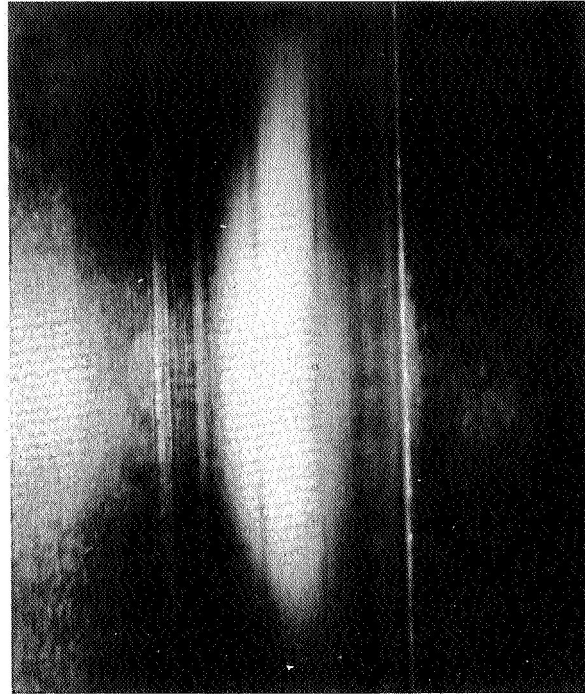


Outer Ring

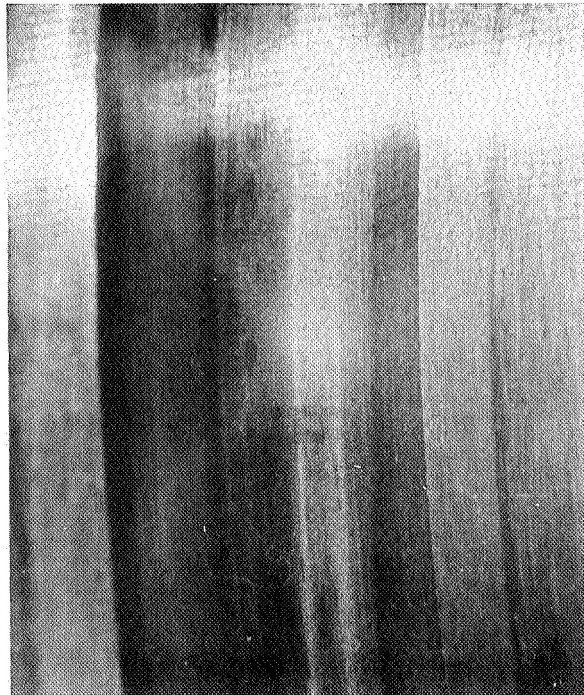
ENCLOSURE 34

7205 VAP Test Bearing #8 (327708)

Lubricant	DuPont Krytox 143AC		
Speed	43,000 rpm		
Total Hours	1.6 @ 300 lbs.		
Test Runs	7A, 7B		
Surface Finish	(microinches A.A.)		
	Inner	Outer	Balls
New	1.4	1.8	1.6
Tested	1.3	1.4	1.5



Inner Ring



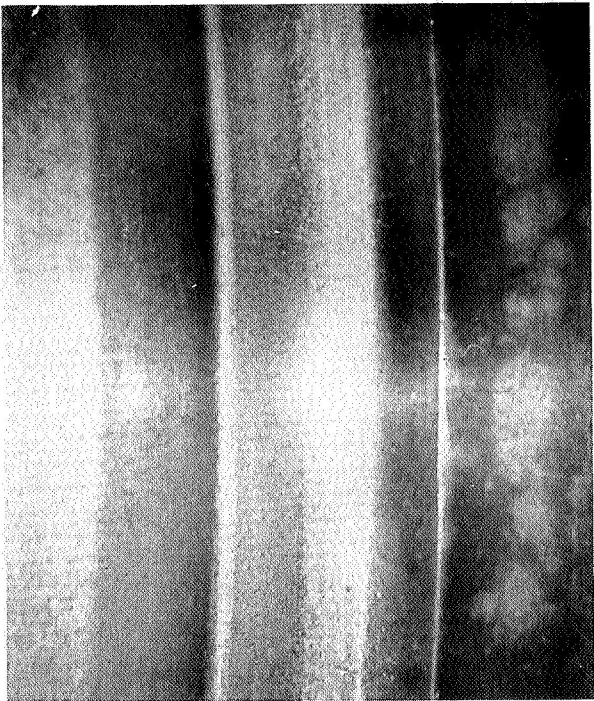
Outer Ring

7205 VAP Test Bearing #9 (327709)

Lubricant DuPont Krytox 143AC
Speed 43,000 rpm
Total Hours 28.4
 a. 2.3 hrs. @ 300 lbs.
 b. 26.1 hrs. @ 459 lbs.

Test Runs 7C, 7D, 7E

Surface Finish (microinches A.A.)
 Inner Outer Balls
New 1.5 1.6 1.6
Tested 1.9 1.7 1.8



Inner Ring



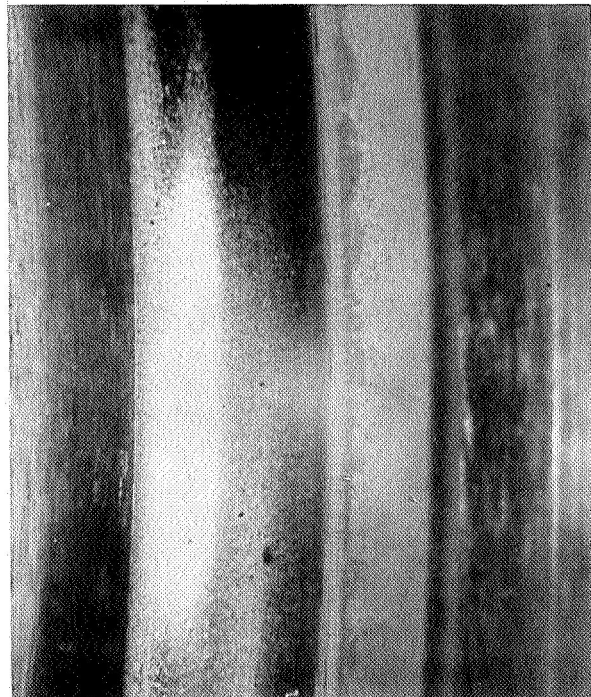
Outer Ring

7205 VAP Support Bearing No. 327505

Lubricant	Mobil XRM-109F
Speed	see below
Total Hours	82.0
a.	23.8 hrs. @ 43,000 rpm & 459 lbs.
b.	36.0 hrs. @ 43,000 rpm & 300 lbs.
c.	14.9 hrs. @ 43,000 rpm & 200 lbs.
d.	7.3 hrs. @ 20,000 rpm & 345 lbs.
Test Runs	1B, 1C, 1D, 1E, 1F, 2A, 2B, 2C, 2D, 2F, 3A, 3E, 3F, 4A, 4B, 4C



Inner Ring

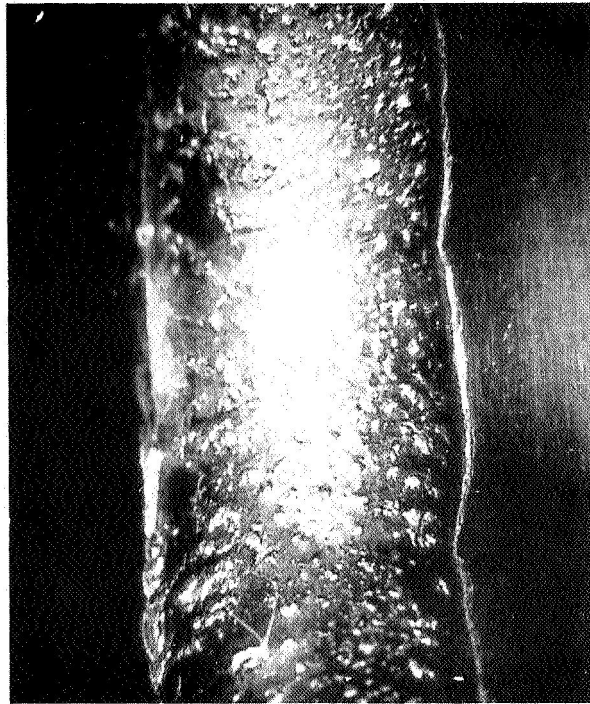


Outer Ring

7205 VAP Support Bearing No. 327801

Lubricant see below
 Speed 43,000 rpm
 Total Hours 21.7
 a. 20.8 hrs. @ 300 lbs.
 1. 12.9 hrs. w/ Turbo S Oil 15
 2. 5.3 hrs. w/ MCS-354
 3. 2.6 hrs. w/ Krytox 143AC
 b. 0.9 hrs. @ 459 lbs. w/ Krytox 143AC

Test Runs 5A, 5B, 5C, 5D, 5E, 5F, 5G
 6A, 6B, 6C, 6D, 6E, 7A, 7B
 7C, 7D, 7E.



Inner Ring

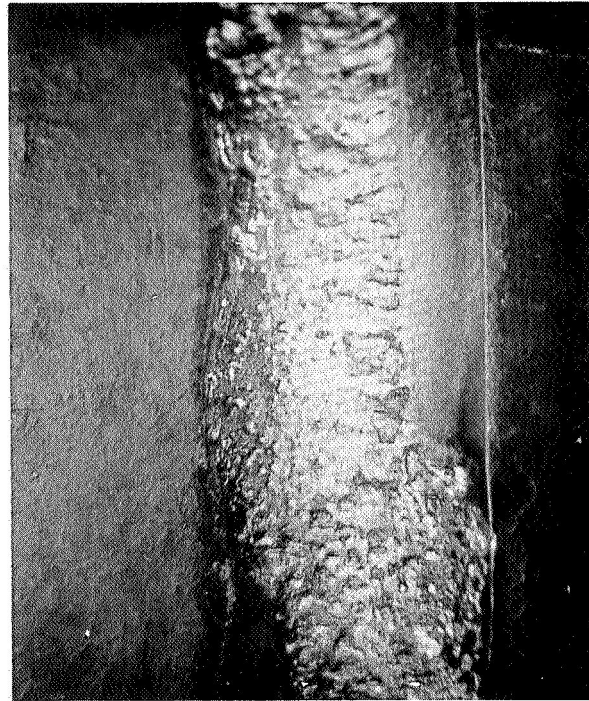


Outer Ring

ENCLOSURE 38

7205 VAP Support Bearing No. 327802

Lubricant DuPont Krytox 143AC
Speed 43,000 rpm
Total Hours 16.8 @ 459 lbs.
Test Runs 7E



Inner Ring



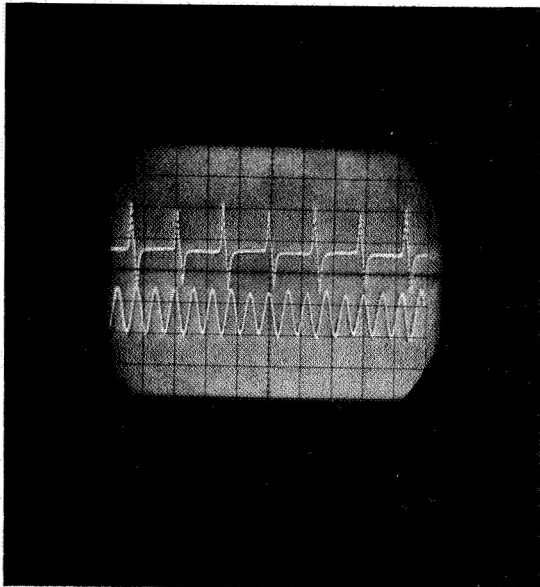
Outer Ring

ENCLOSURE 39

Oscilloscope Traces Obtained in Film Testing With DuPont
Krytox 143AC Lubricant Showing Theoretical Cage Speed

Test Conditions

Speed (inner Ring) - 43,000 rpm
Thrust Load - 459 lbs.
Temperature - 600°F (at outer ring)
T/To across rings $< 1\%$, $\frac{h}{h_0} < 1.8$



inner ring speed trace
(2 cycles per revolution)

cage speed trace
(12 cycles - 12 balls -
per revolution)

Signal trace showing 1 cage revolution (12 cycles)
per 2.5 inner ring revolutions (5 cycles).

Cage/inner ring speed ratio = 40%

Oscilloscope horizontal sweep speed - 0.5 m sec/div.

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 Dept. 93-3
 9851 Sepulveda Blvd.
 Los Angeles, California 90009
 Attention: Hans J. Poulsen

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Alcor Incorporated
 2905 Bandera Road
 San Antonio, Texas 78205
 Attention: Mr. L. Hundere

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Avco Corporation
 Lycoming Division
 550 Main Street
 Stratford, Connecticut 06497
 Attention: M. S. Saboe

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Aerojet-General Corporation
 20545 Center Ridge Road
 Cleveland, Ohio 44116
 Attention: D. B. Rake

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Allegheny Ludlum Steel Corporation
 Oliver Building
 Pittsburgh, Pennsylvania 15222
 Attention: Library

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Boeing Aircraft Company
 Aerospace Division
 Seattle, Washington 98101
 Attention: Materials and Processing Section
 J. W. VanWyk

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Battelle Memorial Institute
 505 King Avenue
 Columbus, Ohio 43201
 Attention: C. Allen

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Borg-Warner Corporation
 Roy C. Ingersoll Research Center
 Wolf and Algonquin Roads
 Des Plaines, Illinois 60016
 Attention: Library

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Curtiss-Wright Corporation
 Wright-Aeronautical Division
 Wood-Ridge, New Jersey 07075
 Attention: S. Lombardo

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California Research Corporation
 Richmond, California 94802
 Attention: Neil Furby
 D. Godfrey

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Crucible Steel Company of America
 Oliver Building, Mellon Square
 Pittsburgh, Pennsylvania 15222
 Attention: Library

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Caterpillar Tractor Company
 Peoria, Illinois 61601
 Attention: B. W. Kelley

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Dow Chemical Company
 Abbott Road Buildings
 Midland, Michigan 48640
 Attention: Dr. R. Gunderson

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Dow Corning Corporation
 Midland, Michigan 48640
 Attention: R. W. Awe
 H. M. Schiefer

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Douglas Aircraft Company
 3000 Ocean Park Blvd.
 Santa Monica, California 90406
 Attention: R. McCord

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E. I. DuPont de Nemours and Company
 Wilmington, Delaware 19898
 Attention: Organic Chemicals Department
 Freon Products Division
 John J. Daly, Jr.

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E. I. DuPont de Nemours & Company
 1007 Market Street
 Wilmington, Delaware 19898
 Attention: George Finn

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ERPT Precision Products Company
 227 Burlington Avenue
 Clarendon Hills, Illinois 60514
 Attention: C. Dean

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Franklin Institute Laboratory
 20th & Parkway
 Philadelphia, Pennsylvania 19103
 Attention: Otto Decker

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Fafnir Bearing Company
 37 Booth Street
 New Britain, Connecticut 06051
 Attention: H. B. Van Dorn

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Fairchild Engine and Airplane Corporation
 Strato Division
 Bay Shore, New York
 Attention: Library

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Gulf Research & Development Company
 P. O. Drawer 2038
 Pittsburgh, Pennsylvania 15230
 Attention: Dr. H. A. Ambrose

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General Electric Company
 General Engineering Laboratory
 Schenectady, New York 12301
 Attention: Library

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General Electric Company
 Gas Turbine Division
 Evendale, Ohio 45202
 Attention: B. Venable
 E. N. Bamberger

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General Motors Corporation
 New Departure Division
 Bristol, Connecticut 06010
 Attention: W. O'Rourke

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General Motors Corporation
 Hyatt Division
 Sandusky, Ohio 44870
 Attention: B. Ruley

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General Motors Research Laboratory
 Warren, Michigan 48090
 Attention: Nils L. Muench

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IIT Research Institute
 West 35th Street
 Chicago, Illinois 60616
 Attention: W. Jamison

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Industrial Tectonics, Inc.
 Research & Development Division
 18301 Santa Fe Avenue
 Compton, California 90220
 Attention: Heinz Hanau

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Lockheed Aircraft Corporation
 Lockheed Missile & Space Co.
 Material Science Laboratory
 3251 Hanover Street
 Palo Alto, California 94301
 Attention: F. J. Clauss

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Mechanical Technology, Inc.
 Latham, New York 14603
 Attention: B. Sternlicht

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Midwest Research Institute
 425 Volker Blvd
 Kansas City, Missouri 64110
 Attention: V. Hopkins
 A. D. St. John

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The Marlin-Rockwell Corporation
 Jamestown, New York 14701
 Attention: A. S. Irwin

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Monsanto Chemical Company
 800 North Lindbergh Blvd.
 St. Louis, Missouri 63166
 Attention: K. McHugh

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North American Aviation Corporation
 Downey, California 90241
 Attention: W. A. Strsalkowski

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Pennsylvania State University
 Department of Chemical Engineering
 University Park, Pennsylvania 16802
 Attention: Dr. E. E. Klaue

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Rocketdyne Division of North American Aviation
 Canoga Park, California
 Attention: Library

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Mobil Oil Corporation
 Paulsboro Laboratory, Research Dept.
 Paulsboro, New Jersey 08066
 Attention: E. Oberright

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Southwest Research Institute
 San Antonio, Texas 78205
 Attention: P. M. Ku

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Steward-Warner Corporation
 1826 Diversey Parkway
 Chicago, Illinois 60614
 Attention: R. F. Wharton

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Timkin Bearing Company
 Canton, Ohio 44701
 Attention: W. Littmann

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United Aircraft Corporation
 Pratt & Whitney Aircraft Division
 East Hartford, Connecticut 06108
 Attention: R. P. Schevchenko
 P. Brown

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Westinghouse Electric Corporation
 Research Laboratories
 Beulah Road, Churchill Borough
 Pittsburgh, Pennsylvania 15235
 Attention: J. Boyd

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